NASA Contractor Report 165840

Design Allowables Test Program, Celion 3000/PMR-15 and Celion 6000/PMR-15, Graphite/Polyimide Composites

J. B. Cushman and S. F. McCleskey

BOEING AEROSPACE COMPANY
SEATTLE, WASHINGTON

CONTRACT NAS1-15644
JUNE, 1982

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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FOREWORD

This document was prepared by the Boeing Aerospace Company for the National Aeronautics and Space Administration, Langley Research Center in compliance with Contract NAS1-15644, "Design, Fabrication and Test of Graphite/Polymide Composite Joints and Attachments for Advanced Aerospace Vehicles."

This report is one of five volumes that will document contract results. It summarizes the results of the Task 1.2.1 "Design Allowables Test." The other four volumes will fully report contract results for Task 1.0 "Design of Attachments" and Task 2.0 "Bonded Joints."

Dr. Paul A. Cooper was the contracting officer's technical representative for the full contract and Gregory Wichorek was the technical representative for design allowables testing of Celion 6000/PMR-15. Boeing performance was under the management of Mr. J. E. Harrison. Mr. D. E. Skoumal was the technical leader. Major participants in this program were Stephen F. McCleskey, Celion 6000/PMR-15 testing; James B. Cushman, Celion 3000/PMR-15 testing; Sylvester G. Hill, Materials and Processes.

Certain materials are identified in this publication in order to specify adequately which materials were investigated. In no case does such identification imply recommendation or endorsement of the material by NASA, nor does it imply that the materials are necessarily the only ones or the best ones available for the purpose.

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1.0 SUMMARY

A design allowables test program was conducted to evaluate graphite polyimide composites over a temperature range of 116K (-250^{o}) to 589K (600^{o}F). A total of 225 tests were conducted on Celion 6000/PMR-15 composites in fulfillment of Task 1.2.1.1 of NASA contract NAS1-15644 as amended. A total of 189 tests were conducted on Celion 3000/PMR-15 composites under Boeing IR&D funds. Tests were conducted to measure tension, compression, flatwise (out-of-plane) tension, in- plane shear, interlaminar shear and coefficient of thermal expansion (CTE) properties.

Celion 3000/PMR-15 laminates were tested at 294K (70^{o}F) and 561 (550^{o}F). Material environmental conditionings evaluated were 1) cured/post-cured; 2) thermally aged; 3) thermally cycled; and 4) moisture saturated. Tension ultimate strength, tangent modulus and Poisson's ratio were determined for 0_{16}, 90_{30}, $(0/\pm45/90)_{4S}$ and $(\pm45)_{8S}$ laminates. Compression ultimate strengths and modulus were measured for a $(90/\pm45/0)_{4S}$ laminate. In-plane shear strength and modulus were measured for a $(\pm45)_{3S}$ laminate. CTE properties were measured for a $(0/\pm45/90)_{4S}$ laminate and a modified high temperature adhesive designated A7F that is described. Flatwise (out-of-plane) tension strengths were measured for a $(0/\pm45/90)_{2S}$ laminate and a $(0/\pm45/90)_{2S}$ laminate bonded to honeycomb core.

Celion 6000/PMR-15 laminates were tested at 116K (-250^{o}F), 294K (70^{o}F), 589K (600^{o}F). Material was evaluated at a conditioning of "baseline dry". Ultimate tension strengths, tangent modulus and Poisson's ratio were determined for 0_8, $(0/+45/90/-45)_S$ and $(\pm45)_{2S}$ laminates. Ultimate compression strength, tangent modulus and Poisson's ratio were determined for 0_{16}, $(0/+45/90/-45)_{2S}$ and $(\pm45)_{4S}$ laminates. In-plane ultimate shear stress and shear modulus were measured for a $(0/+45/90/-45)_S$ laminate. Interlaminar shear strength was measured for a $(0)_{20}$ laminate.

Test results show a consistent material performance over the temperature range and environmental conditions evaluated. Material strengths and stiffnesses were of sufficient magnitude to demonstrate Celion 3000/PMR-15 and Celion 6000/PMR-15 as viable materials for use in structural applications at temperatures up to 589K (600^{o}F).

Celion 6000/PMR-15 laminates had strengths and moduli that varied from 0% to 56% less than Celion 3000/PMR-15 laminates depending on the lay-up and temperature. Moisture saturated specimens had no strength decrease when tested at room temperature. However, rapid heating, .23K/sec (25^{o}F/min), caused blistering of the 561K (550^{o}F) test specimens and subsequent reduction of matrix dominated laminate strengths (up to 62 percent of $(90)_{30}$ when compared with cured/post-cured specimens). The $(0'\pm45'90)_{4S}$ saturated laminate strength was approximately 77 percent of the cured/post-cured laminate capability at 561K (550^{o}F). Thermal cycling produced micro-cracks in $(0/\pm45/90)_S$ laminate. The CTE of A7F adhesive decreased when thermally aged. Test results also show that in-plane shear modulus data for $(0)_N$ and $(0/\pm45/90)_{NS}$ laminates can be determined by simple tension tests using bi-axial strain gages.

2.0 INTRODUCTION

Graphite polymide composites have shown potential for use as a structural material at elevated temperatures on advanced aerospace vehicles. An experimental program to develop several types of graphite/polyimide (GR/PI) bonded and bolted joints was funded under NASA contract NAS1-15644. The program consists of two concurrent tasks. TASK 1 is concerned with design and test of specific built-up attachments, while TASK 2 evaluates standard and advanced bonded joint concepts. The purpose is to develop a data base for the design and analysis of advanced composite joints for use at elevated temperatures (561K (550^{O}F)). The objectives are to idenfity and evaluate design concepts for specific joining applications and to identify the fundamental parameters controlling the static strength characteristics of such joints. The results from these tasks will provide the data necessary to design and build GR/PI lightly loaded flight components for advanced space transportation systems and high speed aircraft. To evaluate graphite/polyimide a design allowables test program was conducted to measure material properties of Celion 6000/PMR-15 composites in fulfillment of Task 1.2.1.1 of the contract. Additional testing was conducted on Boeing Independent Research and Development (IR&D) funds to measure properties of Celion 3000/PMR-15 composites.

This report presents test procedures and results of the Celion 3000/PMR-15 and Celion 6000/PMR-15 design allowables test programs. Tests were conducted to measure tension, compression, flatwise (out of-plane) tension, in-plane shear, interlaminar shear and coefficient of thermal expansion (CTE) properties. Test temperatures for the Celion 3000/PMR-15 were 294^{O}K (70^{O}F) and 561^{O}K (550^{O}F) while specimen conditioning included 1) cured/postcured; 2) thermally aged; 3) thermally cycled; and 4) moisture saturated. Test temperatures for the Celion 6000/PMR-15 were 116^{O}K (-250^{O}F), 294^{O}K (70^{O}F), and 589^{O} K(600^{O}F) with all specimens conditioned to "baseline dry". Test results from these programs were used to design and analyze graphite/polyimide joints. Test data also provide preliminary

design properties for graphite/polyimide composites and demonstrate consistent material performance at elevated temperatures.

This is one in a series of five reports that will fully document the results of design, analysis and test activities performed under NASA contract NAS1-15644. The other reports are:

1. "Design, Fabrication and Test of Graphite/Polyimide Composite Joints and Attachments (TASK 1.0)" - Executive Summary

2. "Design, Fabrication and Test of Graphite/Polyimide Composite Joints and Attachments (TASK 1.0)" - Data Report

3. "Test and Analysis of Celion 3000/PMR-15 Graphite/Polyimide Bonded Composite Joints (TASK 2.0)" - Executive Summary

4. "Test and Analysis of Celion 3000/PMR-15 Graphite/Polyimide Composite Bonded Joints (TASK 2.0)" - Data Report

3.0 PURPOSE

The purpose of this document is to present test procedures and results of the design allowables test programs conducted for Celion 3000/PMR-15 and Celion 6000/PMR-15 graphite/polyimide composites. Testing of Celion 3000/PMR-15 was conducted under Boeing IR&D funds. Testing of Celion 6000/PMR-15 was conducted under Task 1.2.1.1 of NASA Contract NAS1-15644 as amended.

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4.0 MATERIAL AND SPECIMEN FABRICATION

This section describes materials, processing and specimen fabrication procedures used for this program.

4.1 Materials

Composite materials characterized under this program were laminates of graphite fibers preimpregnated with polyimide resin. The polyimide resin was PMR-15 and the graphite fibers were Celanese Corp. Celion 3000 and Celion 6000 with NR-150B2G sizing. Material was procured from U.S. Polymeric Inc., Santa Ana, California, to the material specification in NASA CR 159182 (ref. 3). Special requirements were imposed on the supplier that limited the size of resin batches mixed to 11 Kg (24 lb) maximum. This was to limit the exothermic reaction during mixing. Prepreg material was procured in sufficient quantity to fabricate the required specimens in Matrix 1 (Table 5.1-1) and Matrix 1A (Table 6.1-1) plus approximately 10% spares. Prepreg for each matrix was fabricated from one fiber lot. Because of limits on resin batch size more than one batch of resin was needed to make the required amount of prepreg; however, the prepreg was delivered under one lot number. Quality Control (Q.C.) tests were conducted on any prepreg roll that was made from a different resin batch. Quality control test results for the Celion 3000 and Celion 6000 lots used are given in Table 4.1-1. Chemical characterization tests were also conducted using high pressure liquid chromatography.

Q.C. tests included mechanical property tests and chemical characterization tests as specified in the material specification, NASA CR 159182 (ref. 3). In some cases, material with Q.C. mechanical properties lower than the specification requirements was accepted. This was because of the experimental nature of this material system and the fact that the specification requirements were based on a small sample size. The primary control

for acceptance or rejection of the prepreg was the chemical characterization test of the prepreg resin. Results of these tests were considered the principal indicator of material processabilty.

The high temperature adhesive tested under this program was designated A7F. A7F is a 50:50 resin solids copolymer blend of NASA's LARC 13 adhesive (Supplied by NASA, LaRC) and AMOCO's AI 1130L Amide-Imide. Sixty percent by weight aluminum powder and 5% by weight cab-o-sil is added. The material system is then blended to a uniform consistency. The adhesive was spread on a 2 mil fiberglass scrim to make adhesive film for bonding operations.

4.2 Specimen Fabrication Procedures

All specimens were fabricated using processes and procedures defined in NASA document NASA CR 159182 (ref. 3). The cure cycle used is defined in Table 4.2-1 and Figures 4.2-1 and 4.2-2. Completed panels were inspected using NDI procedures in NASA document NASA CR 159129 (ref. 4). Specimen fabrication flow for the Celion 3000 and 6000 specimens are shown in Figures 4.2-3 and 4.2-4, respectively.

All panels were fabricated and then inspected by C-scan. Once the panels had passed C-scan, the load tabs were bonded on, where applicable, prior to cutting the panel into specimens. Conditioning of the panels, except for moisture conditioning (Celion 3000), and "baseline dry" (Celion 6000) was done prior to cutting them into specimens to avoid edge effects.

Load tabs were glass/polyimide bonded with A7F (LARC 13 Amide-Imide Modified) adhesive. Load tabs for some of the room and low temperature specimens were bonded with a low temperature adhesive to reduce costs.

Honeycomb core used was HEXCEL HRH 327-3/16-8. This is a glass/polyimide core with 4.76mm (3/16 inch) cell size and 128 kg/m^3 (8 lb/ft^3) density. Core was 19mm (.75 inch) thick.

4.3 Effects of Conditioning On Panels

After panel conditioning, test samples were cut and polished and photomicrographs of the sections prepared. Figures 4.3-1 through 4.3-8 compare the extent of microcracking in quasi-isotropic Celion 3000/PMR-15 panels that were conditioned either by thermal aging (125 hours at 589K (600^{o}F)) or by thermal cycling (125 cycles, 116K (-250^{o}F) to 589K (600^{o}F)), with a one-hour hold at 589 (600^{o}F) each cycle. Figures 4.3-1 and 4.3-2 compare typical sections of thermally aged vs. thermally cycled panels; the latter microcracked in the outer layers. Figures 4.3-3 and 4.3-4 show higher magnification views of the same panels. It is evident, from Figures 4.3-1 and 4.3-3 that:

1. the exposure to 589K (600^{o}F) for 125 hours did not result in microcracking
2. the original cure/postcure cycle did not result in microcracking
3. the PMR-15 matrix successfully withstands the high residual stresses that result from cooling down from the 602K (625^{o}F) peak cure/postcure temperature.

However, the thermal cycling does result in microcracking, as evident in Figures 4.3-2 and 4.3-4 and also in 4.3-5 and 4.3-6. The latter pair of photomicrographs are of a less-typical (but nevertheless frequently appearing) area where microcracking was not limited to the surface layers. Figures 4.3-7 and 4.3-8 are photomicrographs of a $(\pm 45)_{8S}$ panel that was subjected to the 125 thermal cycles; a relatively minor amount of microcracking in the outer layers is evident.

Microcracking is attributed to the stresses which result from the difference in CTE (Coefficient of Thermal Expansion) of the fibers and resin. These stresses are higher in cross-plied laminates due to the resulting

biaxial restraint. Other conditions affecting the formation and degree of microcracking include:

1. cooling to lower temperatures (e.g., 116K (-250^{0}F))
2. increase in resin brittleness (correlates with an increase in glass transition temperature (Tg))
3. thermal shock
4. fiber volume
5. microcrack growth due to cycling.

The microcracks do not break any fibers, but they do act as miniature stress concentrators, resulting in some small loss in properties. Material performance similar to that described above would be expected for Celion 6000/PMR-15.

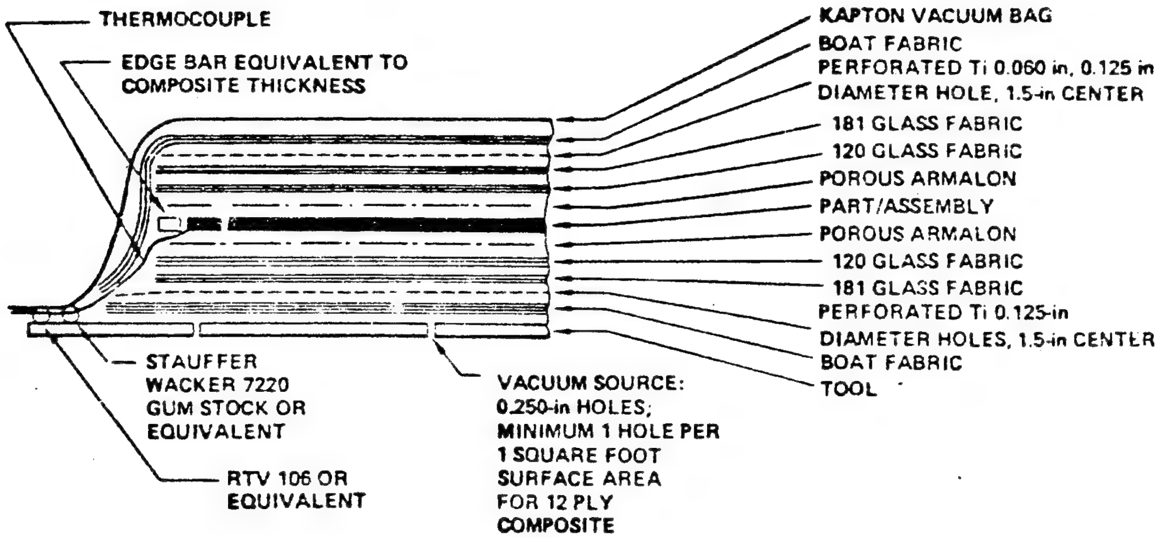
Table 4.3-1 presents data on the change in glass transition temperature (Tg) for Celion 3000/PMR-15 as a result of the thermal aging and thermal cycling conditioning. As expected, the increase in Tg is higher for thermally cycled panels, as their time/temperature exposure includes 125 hours at 589K (600^{0}F) plus the additional elevated temperature exposure during heatup and cooldown. A similar change in T_g for Celion 6000/PMR-15 would be expected.

Table 4.1-1: Quality Control Test Results - Celion 3000 & Celion 6000

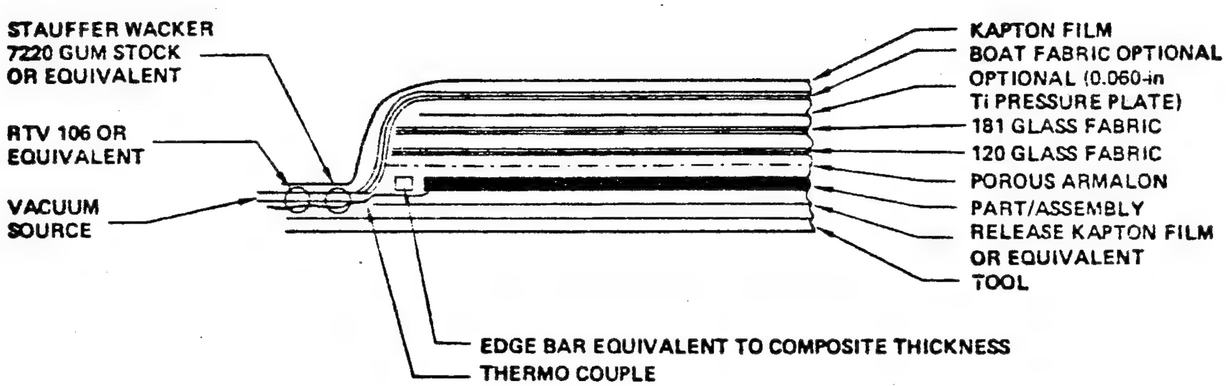
PROPERTY		REQUIREMENTS	Celion 3000/PMR-15 PANEL 2W4582-1R (From Roll #1)	Celion 3000/PMR-15 PANEL 2W4582-2R (From Roll #3)	Celion 6000/PMR-15 LOT 2W4878
Fiber Volume, %		58 ±2	49.5	53.3	58.5
Resin Content, % (by Weight)		30 +3 -1	43.1	39.5	36
Specific Gravity g/cc		1.54	1.530	1.550	1.61
Void Content, %		1.	-0.2	-0.4	1
Flexural Strength MPA (ksi)	At Ambient	1515 (220)	1386 (201)	1586 (230)	1538 (223)
	At 589K (600°F)	757 (110)	931 (135)	958 (139)	827 (120)
	Aged, at 589K (600°F)	757 (110)	938 (136)	1110 (161)	958 (139)
Flexural Modulus GPa (msi)	At Ambient	117 (17)	123 (17.9)	116 (16.9)	123 (19.9)
	At 589K (600°F)	103 (15)	101 (14.7)	103 (14.9)	108 (15.7)
	Aged, at 589K (600°F)	103 (15)	102 (14.8)	104 (15.1)	134 (19.4)
Short Beam Shear Strength MPa (ksi)	At Ambient	96 (14)	101 (14.7)	101 (14.6)	92 (13.3)
	At 589K (600°F)	41 (6)	68 (9.9)	63 (9.2)	59 (8.5)
	Aged, at 589K (600°F)	41 (6)	63 (9.1)	59 (8.5)	59 (8.6)

Table 4.2-1 Celion 3000/PMR-15 and Celion 6000/PMR-15
Cure Cycle Requirements

1. Place layup (Figure 4.2-1) in an autoclave and attach a vacuum source capable of maintaining 100-170mm (4-6 inches) Hg vacuum level.
2. Heat the part/assembly to 463 +5,-0 K (375+10,-0 ^{0}F) at the rate of 2.0-3.0 K (4-6^{0}F) per minute. Change heating rate at 463 +5,-0 K (375 +10,-0 ^{0}F) to 1.1-1.7K (2-3^{0}F) per minute to 522 $\pm$5 K (480 $\pm$10 ^{0}F). See Fig. 4.2-2.
3. After the part/assembly has been held for 30 minutes at 522 +5,-0 K (480 +10,-0^{0}F), apply 650mm (24 inches) vacuum minumum and 1379 Pa (200 psi) positive pressure for the remainder of the cure cycle.
4. After the 1379 Pa (200 psi) positive pressure has been applied, heat part/assembly at the rate of 1.5-2.5 K (3-5^{0}F) per minute to 602 +0, -2.2 K (625 +0,-10^{0}F). Hold at 602 K (625^{0}F) under pressure for 120 +10,-0 minutes. See Fig. 4.2-2.
5. Cool the part/assembly under pressure at the maximum of 1.1K (2^{0}F) per minute. See Fig. 4.2-2.
6. When the part temperature falls below 322K (120^{0}F) pressure can be released and the part removed from the autoclave.
7. After removal of the part/assembly from vacuum bag, postcure in an air circulating oven 6 hours at 602K (625^{0}F). (Note: Part shall be restrained during postcure cycle with Armalon release fabric and minimum of 3 piles 181 glass fabric in contact with part/assembly.) Heat up rate to 602K (625^{0}F) shall be 2.0-3.0K (4-6^{0}F) per minute with the cool down rate not to exceed 1.1K (2^{0}F) per minute. Part/assembly temperature shall not exceed 322^{0}K (120^{0}F) before restraining devices are removed.



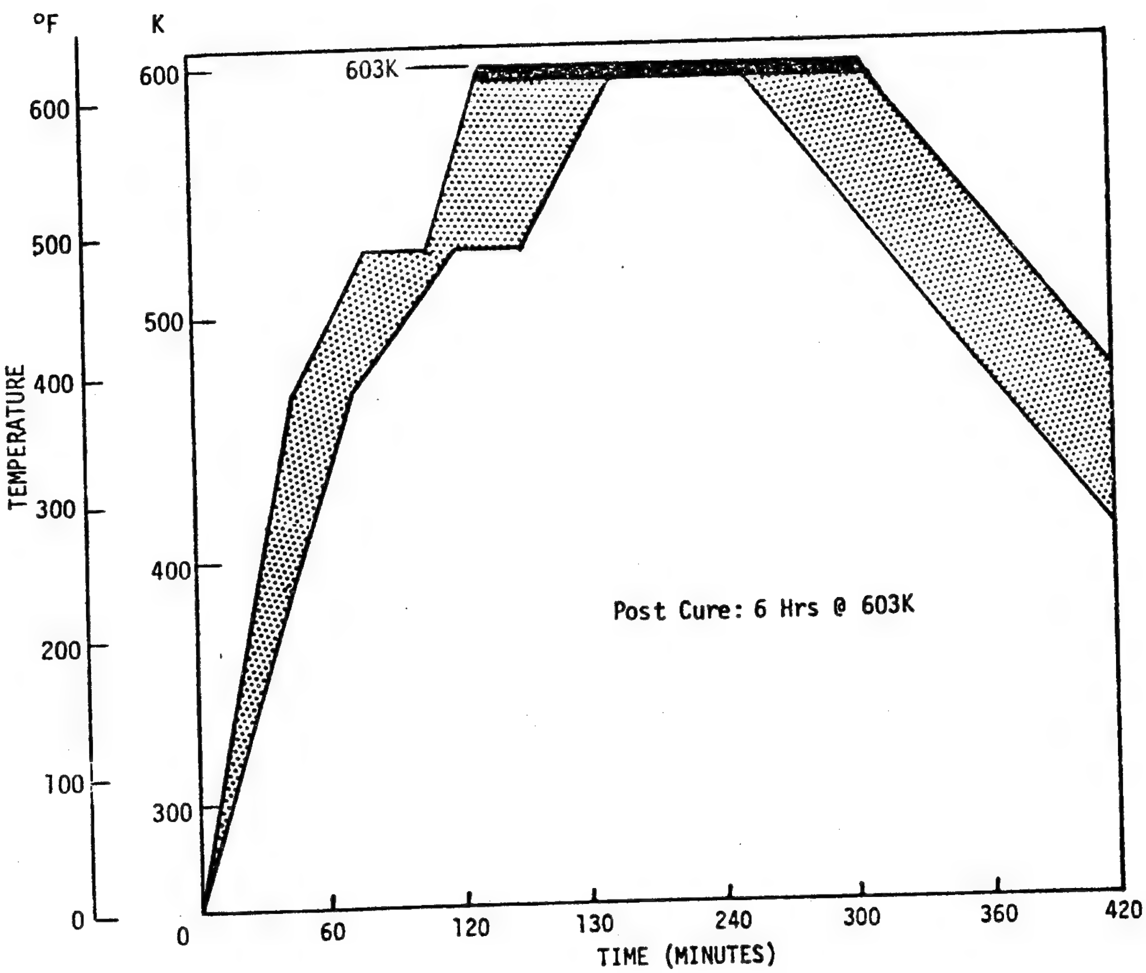
Double Bleed System* for Composites
per NASA CR 159182



Top Bleed System for Composites
per NASA CR 159182

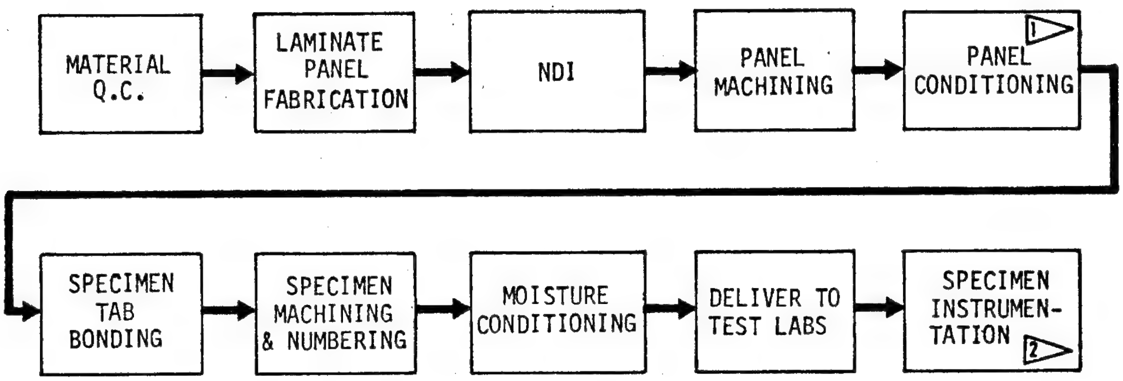
* DOUBLE BLEEDER SYSTEM REQUIRED ON PARTS EXCEEDING 9 SQ. FT. OF 8 PLY LAMINATE. 6 SQ. FT OF 12 PLY LAMINATE, AND 1 SQ. FT. OF 24 PLY LAMINATE.

Figure 4.2-1: Bleed System for Composites



Cure Cycle Graphite/PMR-15 Graphite Polyimide prepreg
per NASA CR 159182

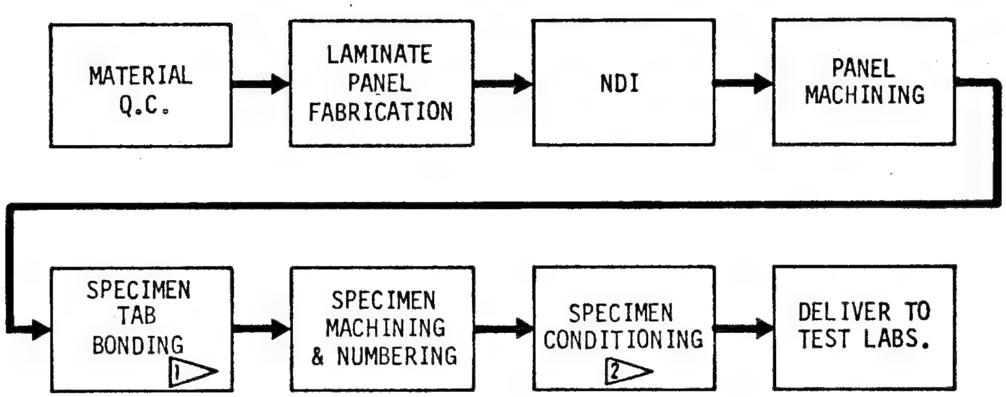
Figure 4.2-2: Graphite/PMR-15 Composite Cure Cycle



1 Except for moisture conditioning.

2 Moisture condition specimens for Test 6 had strain gages installed prior to conditioning.

Figure 4.2-3: Specimen Fabrication Flow - Celion 3000/PMR-15



1 Specimen for tests 1 thru 6 only.

2 Specimens requiring strain gages were instrumented prior to conditioning

Figure 4.2-4: Specimen Fabrication Flow - Celion 6000/PMR-15

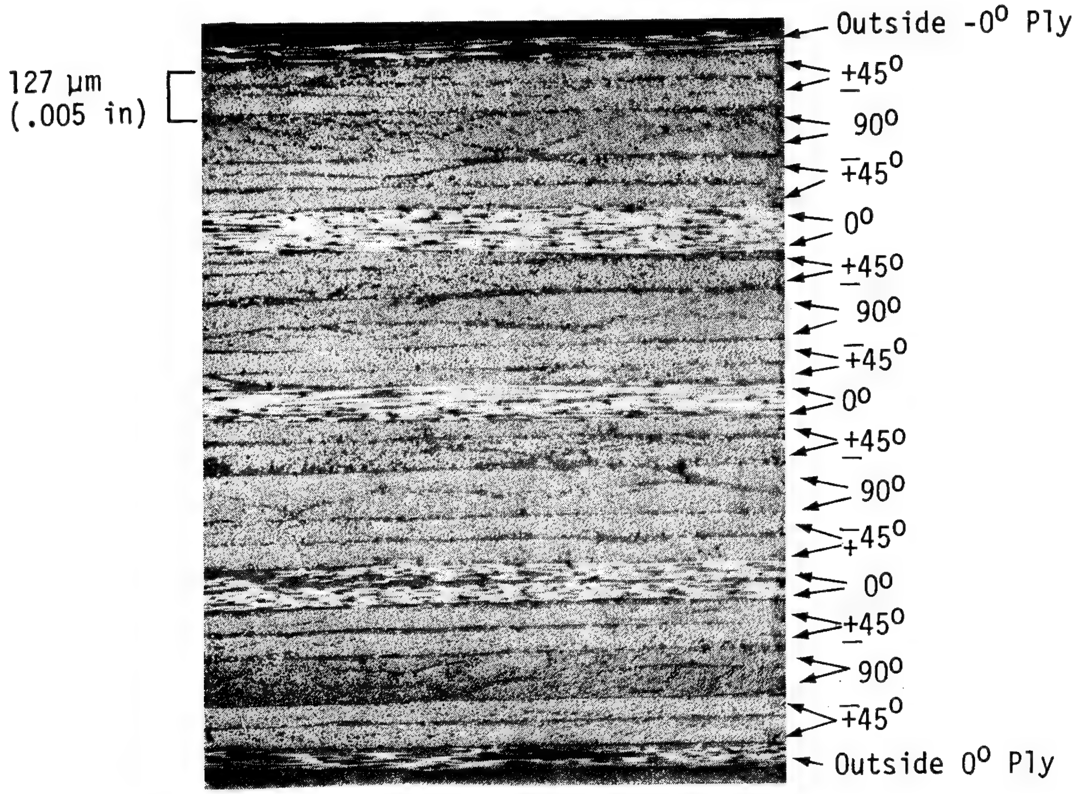


Figure 4.3-1: 2W4582-14B $(0,\pm45,90)_{4S}$, Condition 2, Aged

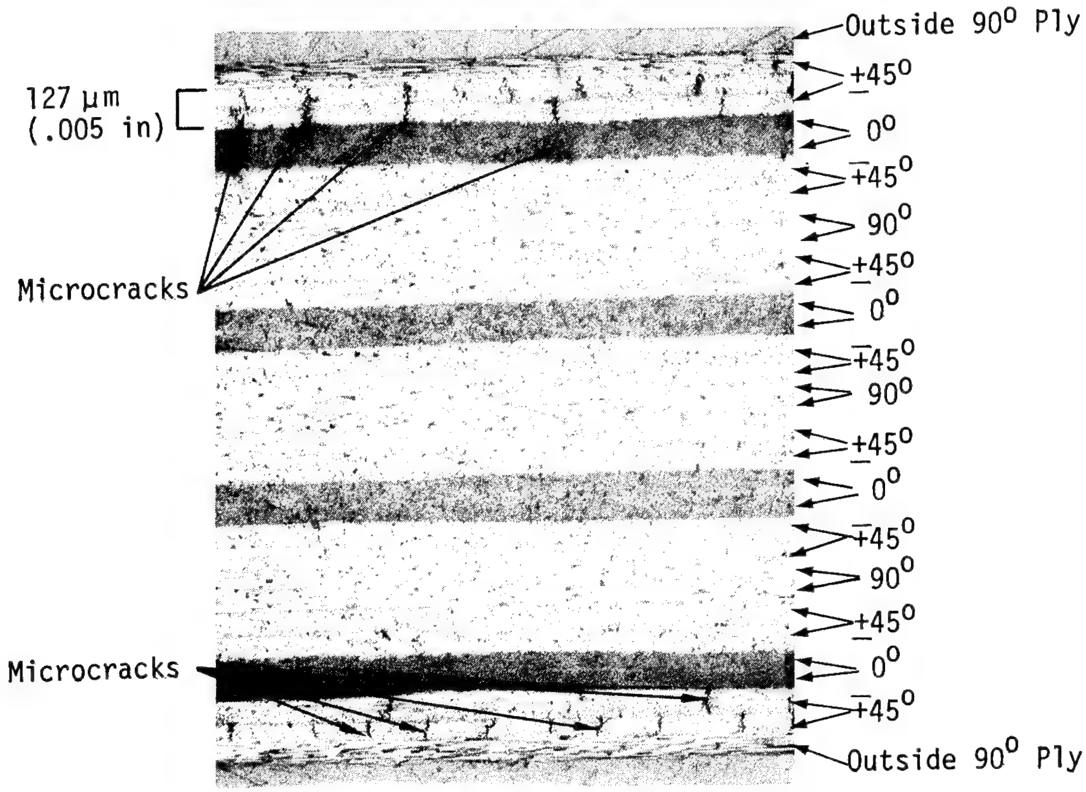


Figure 4.3-2: 2W4582-13B $(90,\pm45,0)_{4S}$, Condition 3, Cycled

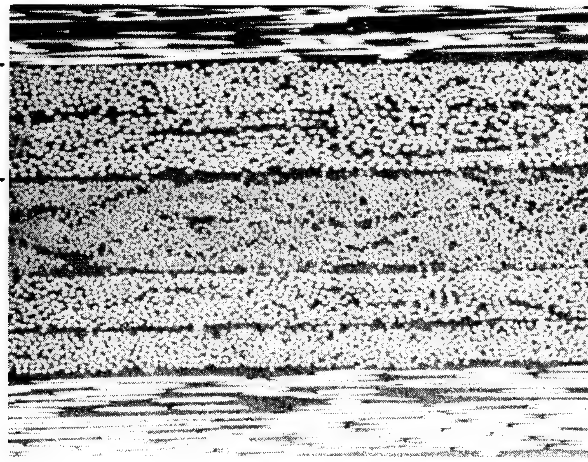


Figure 4.3-3: 2W4582-14B $(0,\pm45,90)_{4S}$, Condition 2, Aged

Figure 4.3-4: 2W4582-13B $(90,\pm45,0)_{4S}$, Condition 3, Cycled

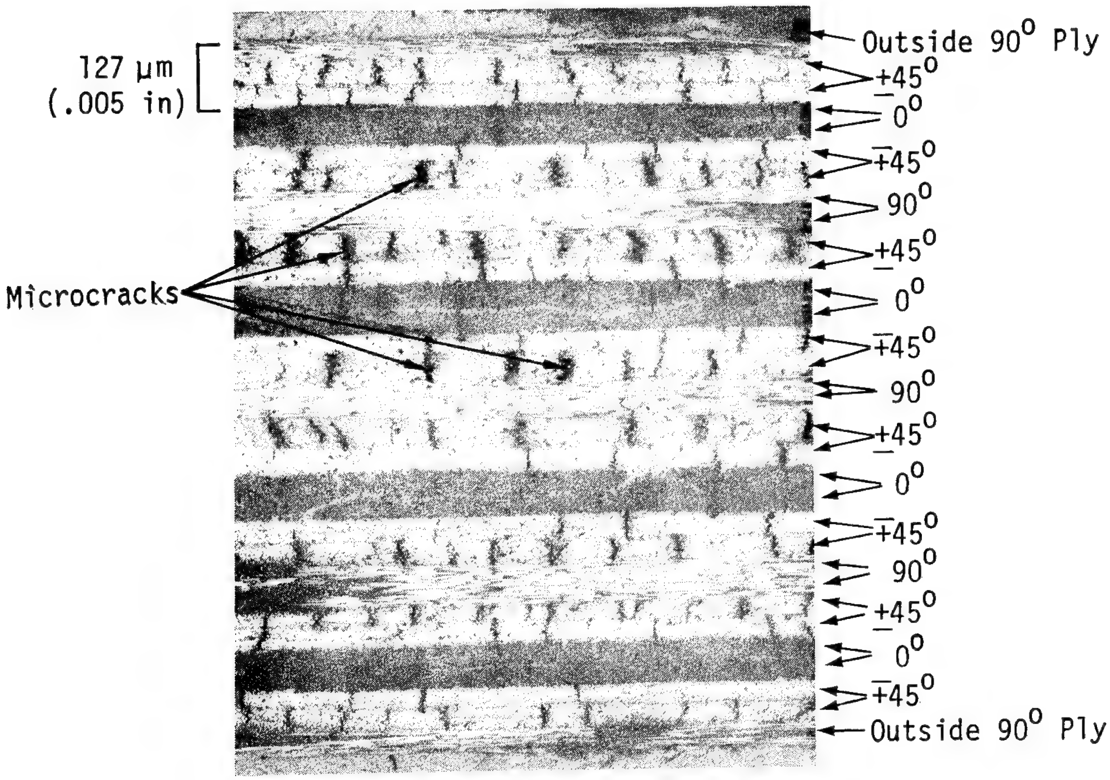


Figure 4.3-5: 2W4582-13B $(90,\pm45,0)_{4S}$, Condition 3, Cycled

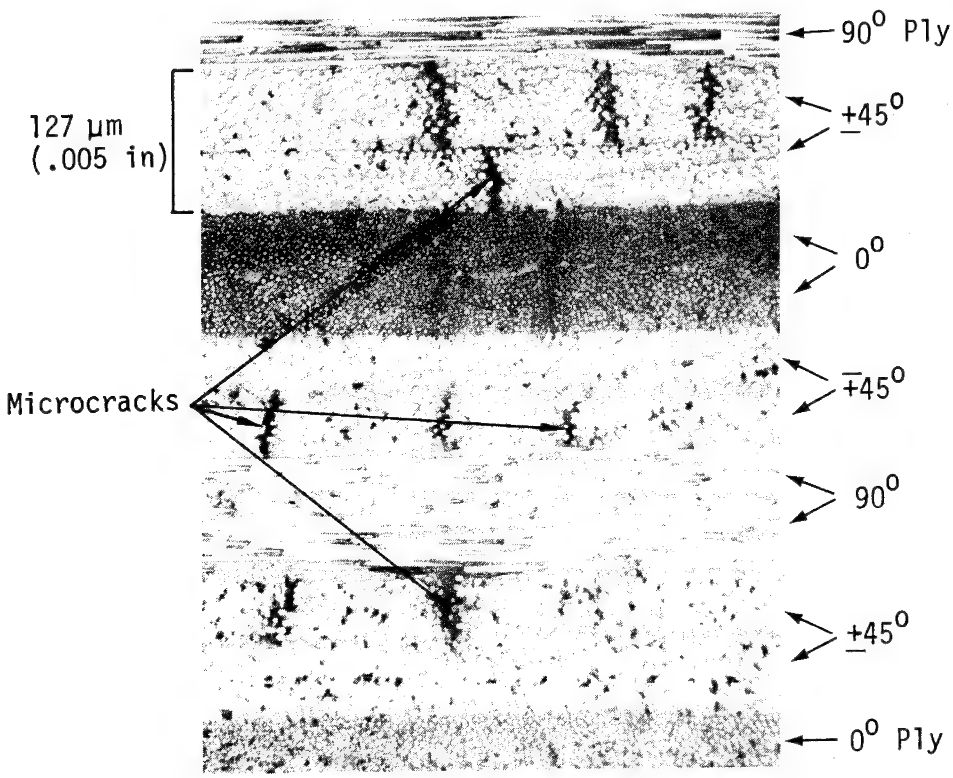


Figure 4.3-6: 2W4582-13B $(90,\pm45,0)_{4S}$, Condition 3, Cycled

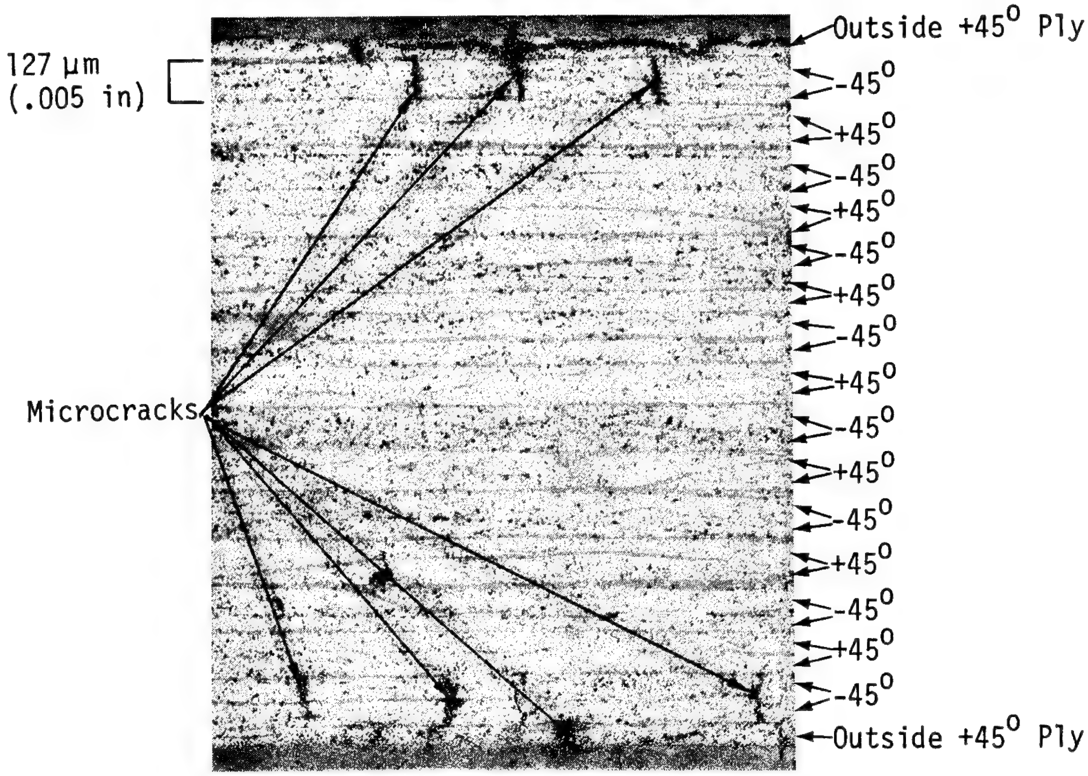


Figure 4.3-7: 2W4582-11B $(\pm 45)_{8S}$, Condition 3, Cycled

Figure 4.3-8: 2W4582-11B $(\pm 45)_{8S}$, Condition 3, Cycled

Table 4.3-1: Effect of Laminate Conditioning on Tg
Celion 3000/PMR-15

Panel No.	As Cured/Postcured	After Aging	After Cycling
2W4582-7	619K (655°F)	---	626K (667°F)
2W4582-10	614K (646°F)	624K (664°F)	---
2W4582-13	621K (658°F)	---	639K (691°F)
2W4582-14	611K (640°F)	620K (657°F)	---

5.0 CELION 3000/PMR-15 TESTING

This section presents the test matrix, specimen configurations, test procedures and test results for all testing of Celion 3000/PMR-15 laminates and A7F adhesive. Also included is a data summary showing averages and coefficient of variations for each test type. The fiber volume of the Celion 3000/PMR-15 specimen was taken to be 51.4%. This was based on the average of the fiber volumes of the quality control panels (Table 4.1-1).

The following test procedures were common to all tests: specimen temperatures were controlled using procedures described in section 5.2; all critical specimen dimensions were measured and recorded prior to test; load versus strain or deflection was recorded using a Balwin recorder; specimen number, dimensions, test temperature and ultimate failure load were recorded on test laboratory data sheets.

5.1 Test Matrix and Specimen Configuration

The design allowables test matrix for Celion 3000/PMR-15, Matrix 1, is shown in Table 5.1-1. Specimen configurations are shown in Figures 5.1-1 through 5.1-9. Those specimens that were strain gaged are shown in Table 5.1-2. Strain gage locations are shown in Figures 5.1-10 through 5.1-12. Note that Celion 6000/PMR-15 was substituted for Celion 3000/PMR-15 for test 5 (sandwich beam compression of a $(0/\pm45/90)_S$ laminate). Included in Matrix 1 are CTE tests for the A7F adhesive.

The test matrix was established to evaluate effects of temperature and environmental conditioning on material performance. Environmental conditions evaluated were cured/postcured, thermally aged, thermally cycled and moisture saturated. Test temperature and conditioning environments are defined in Matrix 1, Table 5.1-1.

5.2 Test Temperatures

Test temperatures for the Celion 3000/PMR-15 tests were controlled as follows:

Room temperature tests were conducted in the normal laboratory environment (nominally 294^{0}K (70^{0}F)). No special environmental conditioning was used.

For the elevated temperature tests (561^{0}K (550^{0}F) the specimens were placed in an enclosure as shown in Figure 5.2-1 that was electrically heated using resistance heating elements. No radiation shield was used to protect the specimens from direct thermal radiation. Temperatures were controlled to ± 6K ($\pm 10^{0}$F) by placing thermocouples on the specimens which were connected to a Thermac Model 624A temperature controller.

For the 116^{0}K (-250^{0}F) tests, specimens were placed in an enclosure as shown in Fig. 5.2-2 that was cooled by evaporating liquid nitrogen. Temperatures were controlled to ± 6K ($\pm 10^{0}$F) by placing thermocouples on the specimens which were connected to an electro-pneumatic controller that pumped in the liquid/gaseous nitrogen.

All specimens were brought to temperature and then soaked for 10 minutes prior to test except for moisture conditioned specimens which were soaked for 5 minutes.

Table 5.1-1: Test Matrix I - Design Allowables Celion 3000/PMR-15

TEST No.	TEST TYPE	LAMINATE ORIENTATION	CONDITIONING [1]	NUMBER OF TESTS AT RT	NUMBER OF TESTS AT 561K (550°F)	NUMBER OF TESTS AT 116K (-250°F)	TOTAL NUMBER OF SPECIMENS	SPECIMEN CONFIGURATION
1	TENSION	0°_{16}	1 2 3	3 3 5	3 3 5		6 6 10	Figure 5.1-1
2	TENSION	90°_{30}	1 2 3 4	3 3 5 3	3 3 5 3		6 6 10 6	Figure 5.1-2
3	TENSION	$(0/\pm45/90)_{4S}$	1 2 3 4	3 3 5 0	3 3 5 5		6 6 10 5	Figure 5.1-3
4	COMPRESSION	$(90,\pm45,0)_{4S}$	1 2 3	3 3 5	3 3 5		6 6 10	Figure 5.1-4
5	COMPRESSION (SANDWICH BEAM)	$(0/\pm45/90)_S$	2	6	6		12	Figure 5.1-5
6	SHEAR (TENSION TEST)	$(\pm45)_{8S}$	1 2 3 4	3 3 5 3	3 3 5 3		6 6 10 6	Figure 5.1-6
7	FLATWISE TENSION (LAMINATE)	$(0/\pm45/90)_{2S}$	1 2	3 3	3 3	3 3	9 9	Figure 5.1-7
8	FLATWISE TENSION (H/C CORE)	$(0/\pm45/90)_{2S}$	1 2	3 3	3 3	3 3	9 9	Figure 5.1-8
9	CTE	ADHESIVE [2]	1 2	2 2	TESTS CONDUCTED FROM 116K (-250°F) TO 589K (600°F)		2 2	PER PROCEDURES
11	CTE	$(0/\pm45/90)_{4S}$	1 2 3	2 2 2			2 2 2	PER PROCEDURES
13	RAIL	$(\pm45)_{3S}$	1 2	3 2	3 2		6 4	Figure 5.1-9

[1] CONDITION CODE

1 - As cured/postcured

2 - Soaked for 125 hrs at 589K (600°F) in a one (1) atomosphere environment (air)

3 - Thermally cycled 125 times in a temperature range from 116K to 589K (-250°F to 600°F) and in a one (1) atmosphere environment (air)

The cryogenic temperature of 116K (-250°F) shall be held for one-half (1/2) hrs and the maximum temperature of 589K (600°F) shall be held for one (1) hr per cycle. The heat-up and cool-down rates shall be approximately 8.3K/min (15°F/min)

4. Moisture Conditioned - Condition in a chamber maintained at 222 ± 6K (140°F ± 10°F) and 95% relative humidity at atmospheric pressure until specimen is saturated.

[2] A7F (LARC-13, Amide-Imide modified) Adhesive film cured into bulk neat resin specimens.

Table 5.1-2: CELION 3000/PMR-15 TEST MATRIX 1 STRAIN GAGED SPECIMENS

TEST NO.	TEST TYPE	LAMINATE LAYUP	CONDITIONING CODE [1]	NO. OF STRAIN GAGED SPECIMENS AT [2] RT	NO. OF STRAIN GAGED SPECIMENS AT [2] 550°F	TOTAL NUMBER OF STRAIN GAGED SPECIMENS	STRAIN GAGE LOCATIONS
1	TENSION	0_{16}	1 2 3	- - 2	- - 2	- - 4	Figure 5.1-10
2	TENSION	$90^{\circ}{}_{30}$	1 2 3 4	- - 2 -	- - 2 -	- - 4 -	
3	TENSION	$(0,\pm45,90)_{4S}$	1 2 3 4	- - 2 -	- - 2 -	- - 4 -	
5	COMPRESSION (SANDWICH BEAM)	$(0,\pm45,90)_S$*	2	2	2	4	Figure 5.1-11
6	SHEAR (BY TENSION)	$(\pm45)_{8S}$	1 2 3 4	- 1 2 3	- 1 - 3	- 2 2 6	Figure 5.1-10
10	SHEAR (BONDED RAILS)	$(\pm45)_{3S}$	1 2	3 2	3 2	6 4	Figure 5.1-12

[1] CONDITION CODE

1 - As Cured/postcured

2 - Soaked for 125 hrs at 600°F in a one (1) atmosphere environment (air)

3 - Thermally cycled 125 times in a temperature range from -250°F to 600°F and in a one (1) atmosphere environment (air)

The cryogenic temperature of -250°F shall be held for one-half (1/2) hrs and the maximum temperature of 600°F shall be held for one (1) hr per cycle. The heat-up and cool-down rates shall be approximately 15°F/min

4 - Moisture Conditioned - Condition in a chamber maintained at 140°F ± 10°F and 95% relative humidity at atmospheric pressure until specimen is saturated.

* Celion 6000/PMR-15

[2] Strain gaged specimens are included in total specimens in Matrix 1, Table

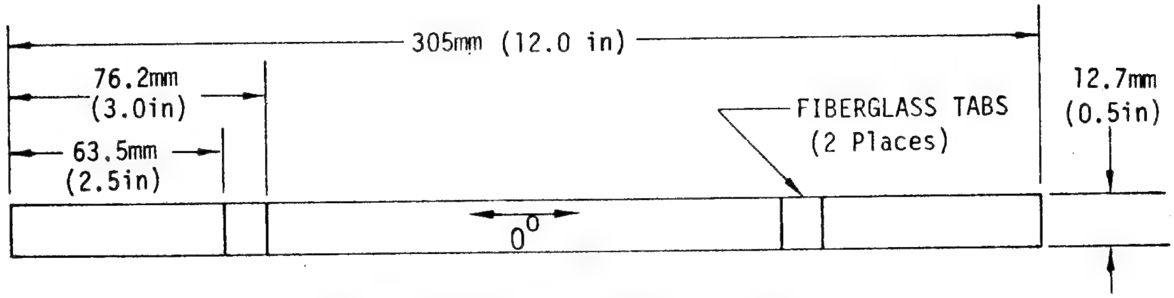


Figure 5.1-1 : Celion 3000/PMR-15 Design Allowables Test No. 1, 0°_{16} Tension Specimen

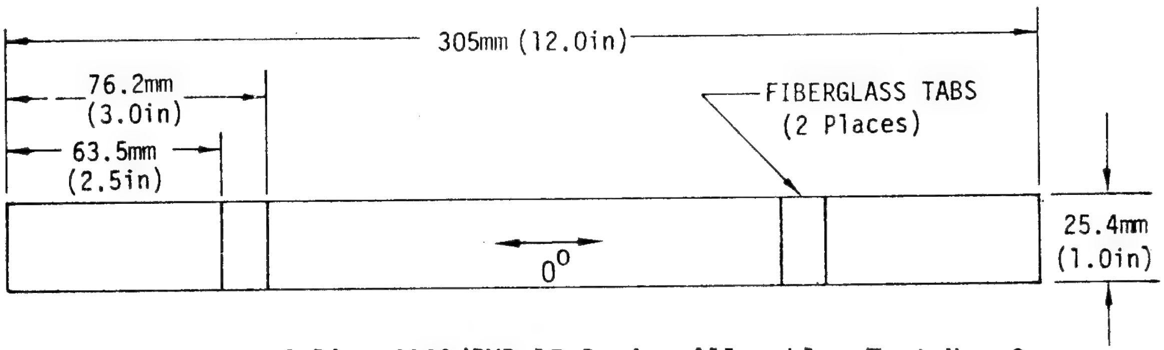


Figure 5.1-2 : Celion 3000/PMR-15 Design Allowables Test No. 2, 90°_{30}, Tension Specimen

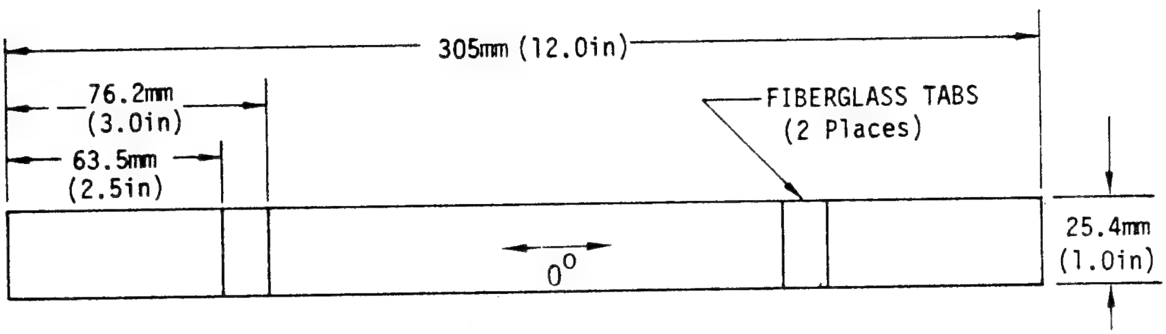


Figure 5.1-3 : Celion 3000/PMR-15 Design Allowables Test No. 3, $(0,\pm45,90)_{4s}$, Tension Specimen

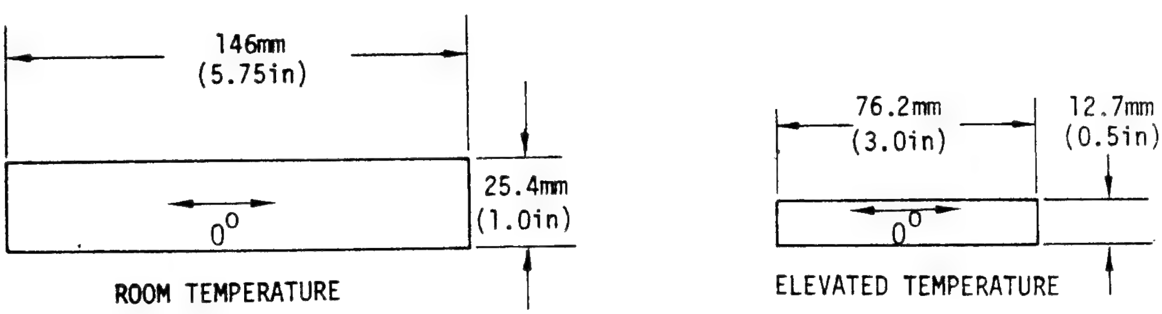
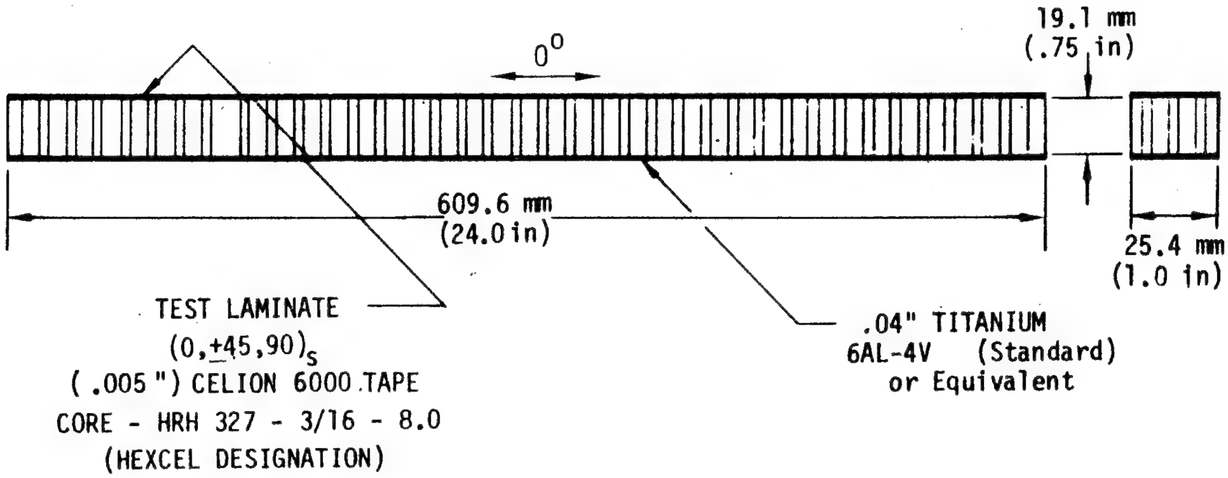


Figure 5.1-4 : Celion 3000/PMR-15 Design Allowables Test No. 4, $(90,\pm45,0)_{4s}$, Compression Specimen



* Celion 6000/PMR-15 Substituted for Celion 3000/PMR-15

Figure 5.1-5 : Celion 6000/PMR-15 Design Allowables Test No. 5, Sandwich Beam Specimen*

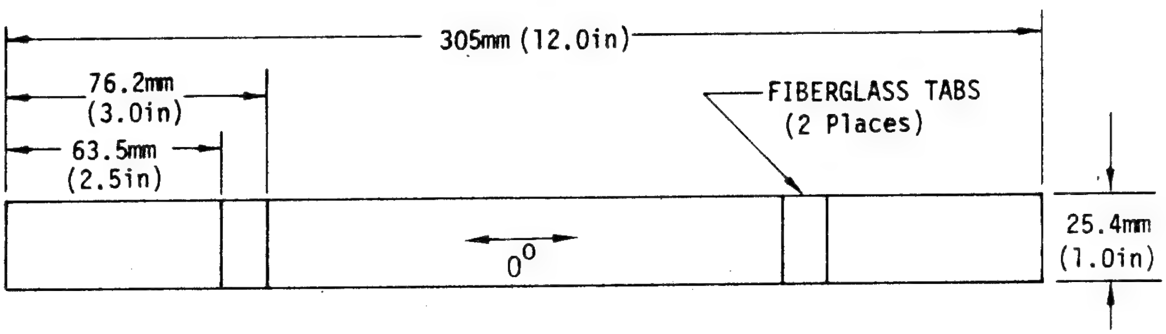


Figure 5.1-6 : Celion 3000/PMR-15 Design Allowables Test No. 6, $\pm45^\circ_{8s}$, Tension Specimen

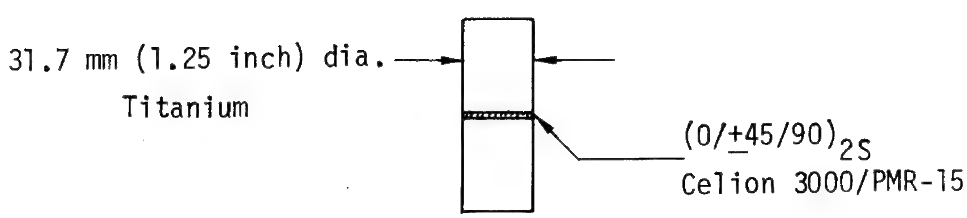


Figure 5.1-7 : Celion 3000/PMR-15 Design Allowables Test No. 7, Flatwise Laminate-to-Laminate Tensile Specimen

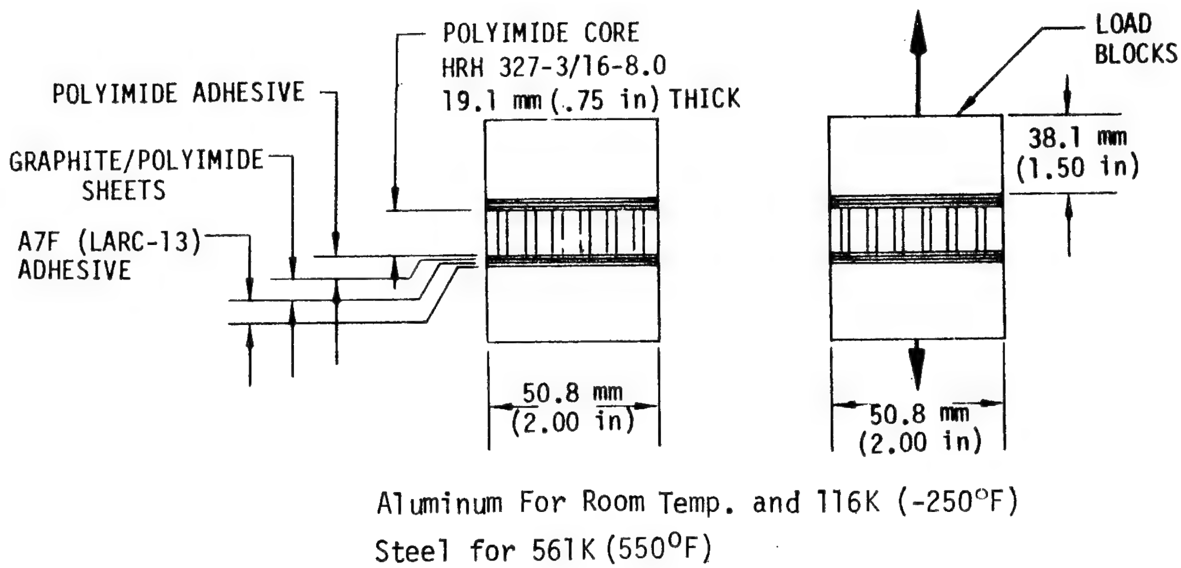


Figure 5.1-8 : Celion 3000/PMR-15 Design Allowables Test No. 8, Flatwise Laminate-to-Core Tensile Specimen

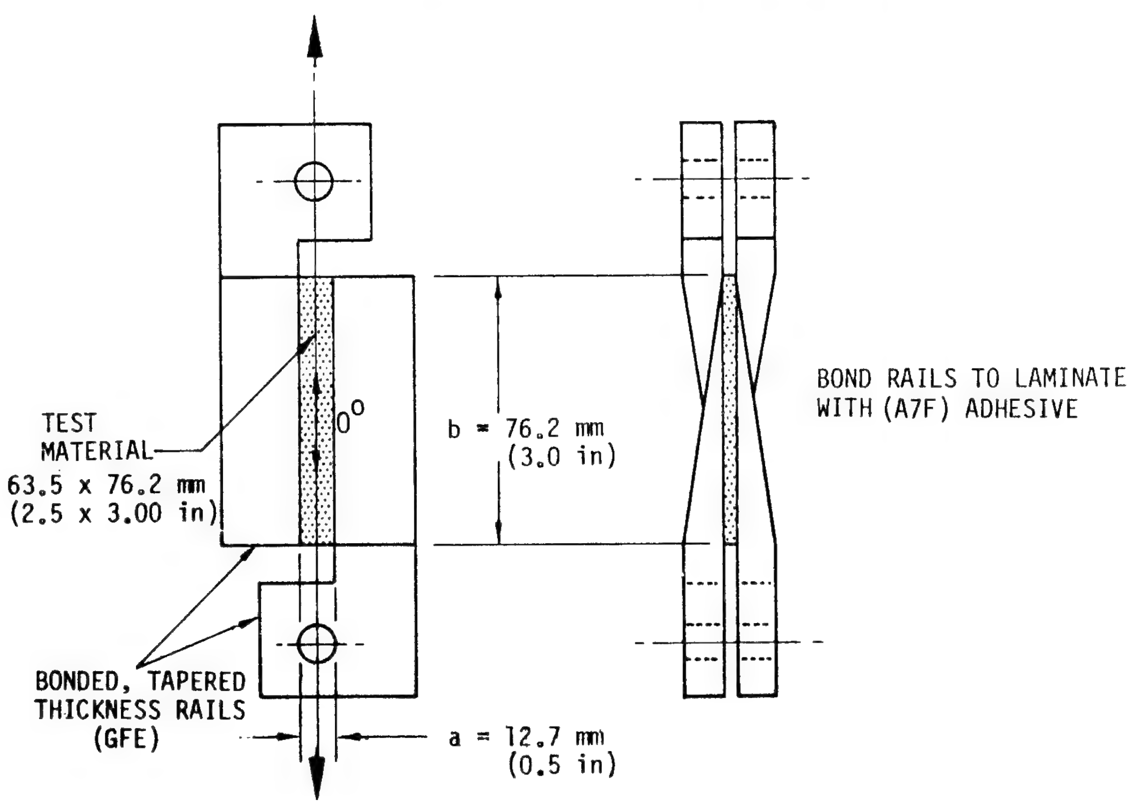


Figure 5.1-9 : Celion 3000/PMR-15 Design Allowables Test No. 13, Rail Shear Specimen

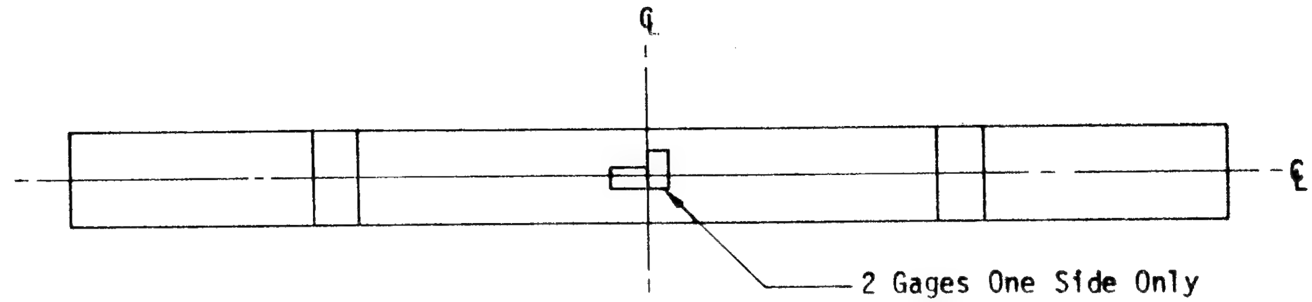
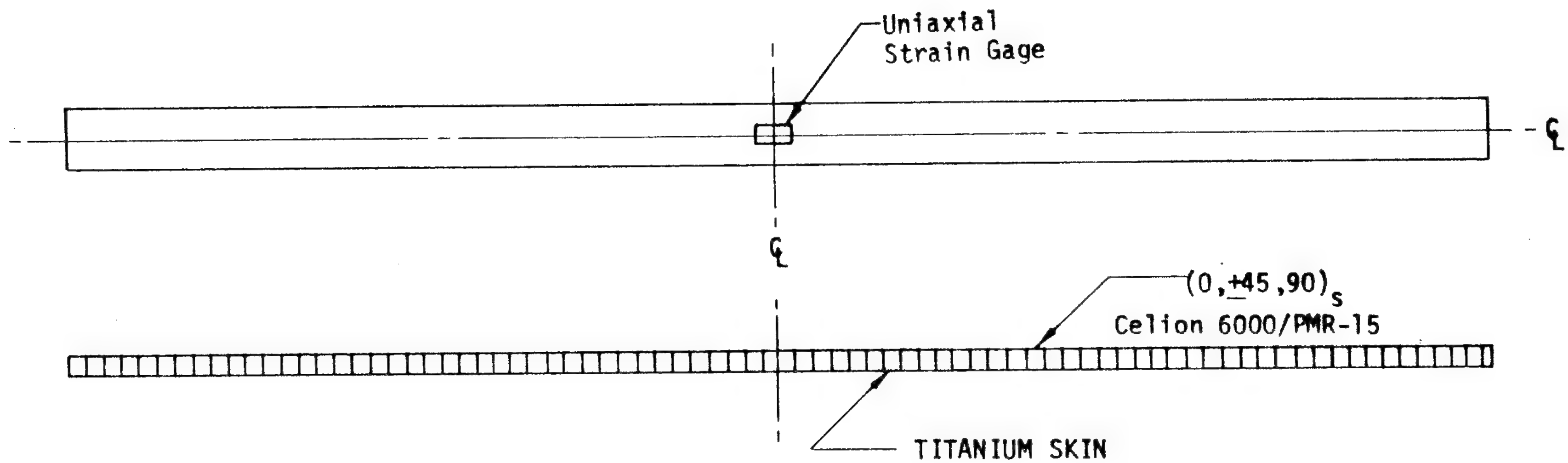


Figure 5.1-10: Strain Gage Locations: Tests 1, 2, 3 and 6 Celion 3000/PMR-15 Design Allowables



* Celion 6000/PMR-15 Was Substituted for Celion 3000/PMR-15

Figure 5.1-11: Strain Gage Location: Test 5* Celion 6000/PMR-15 Design Allowables

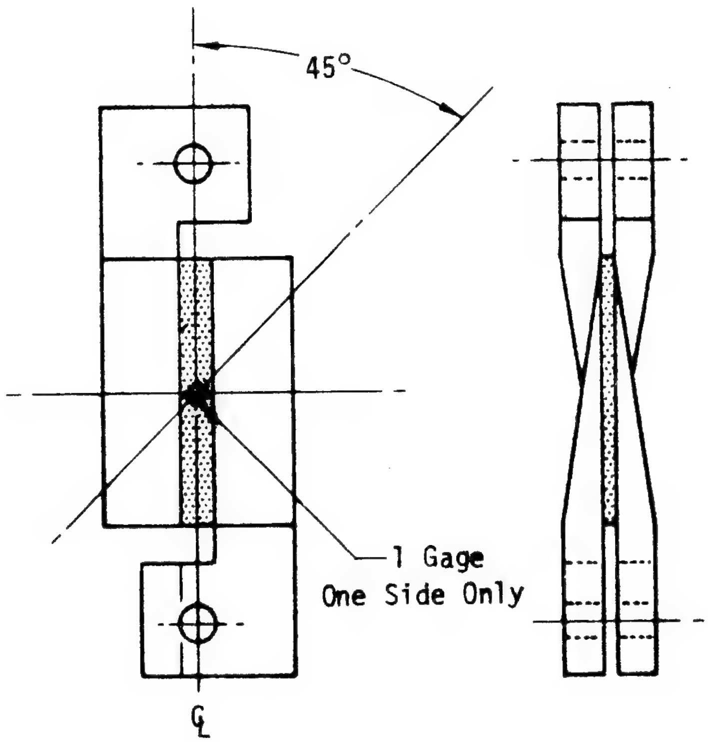


Figure 5.1-12: Strain Gage Location:
Test 13 Celion 3000/PMR-15 Design Allowables

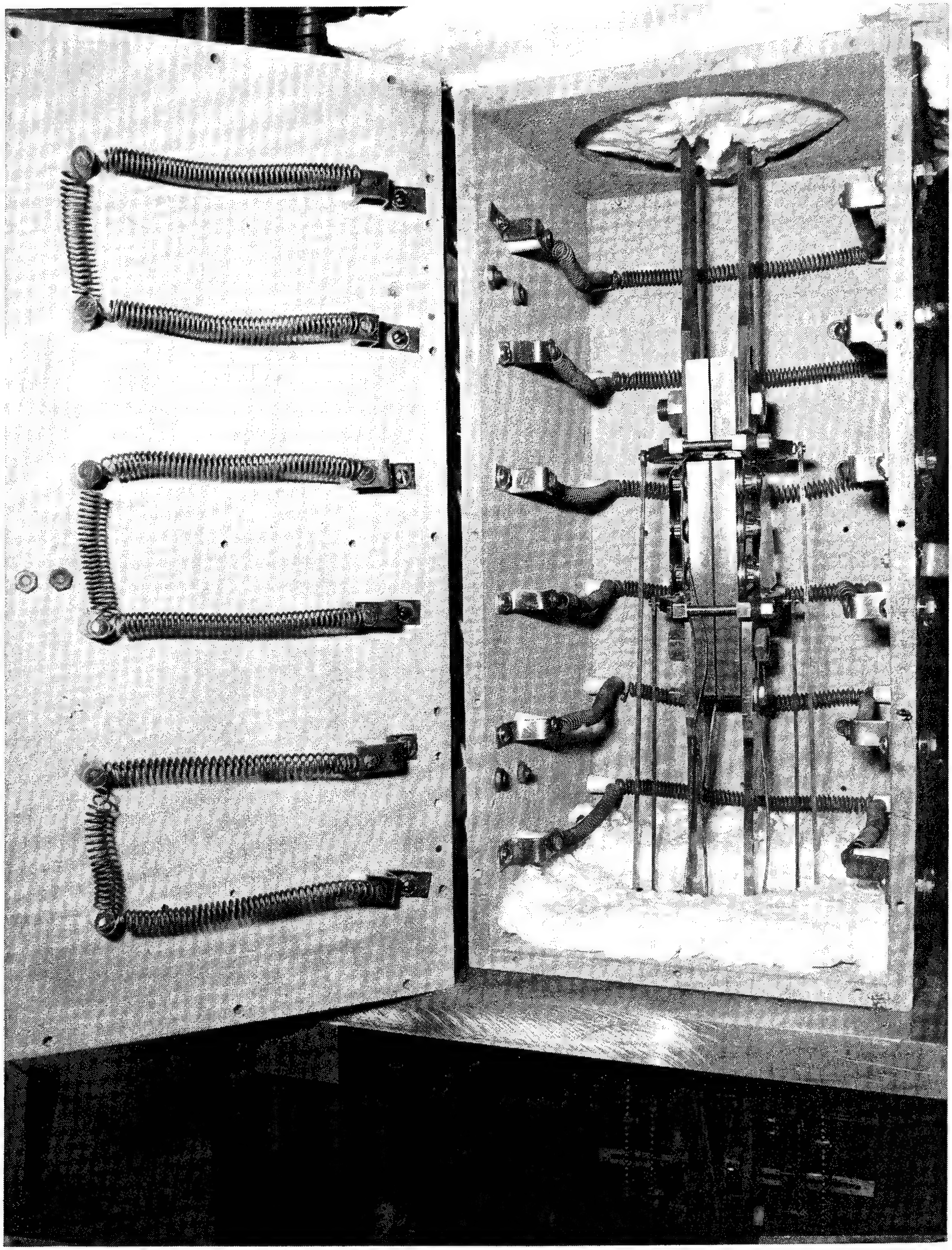


Figure 5.2-1: Elevated Temperature Enclosure
Celion 3000/PMR-15 Design Allowables

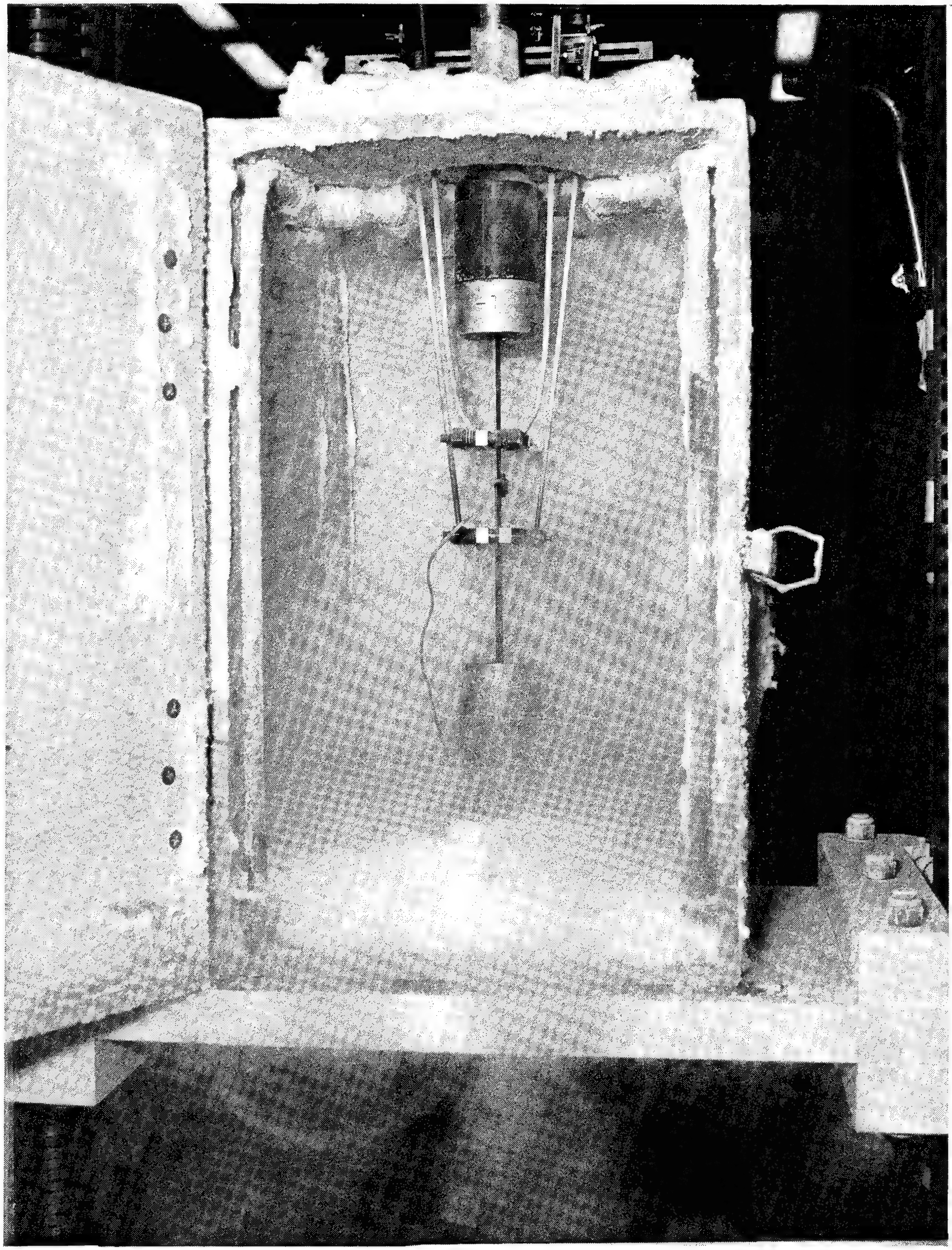


Figure 5.2-2: Reduced Temperature Enclosure
Celion 3000/PMR-15 Design Allowables

5.3 Tension Tests

This section presents test procedures and test results for tension tests of $0^0{}_{16}$, $90^0{}_{30}$, $(0/\pm 45/90)_{4S}$ and $(\pm 45)_{8S}$ laminates.

5.3.1 Test Procedures

Tension tests (tests 1, 2, 3, and 6 of Matrix 1) were conducted in accordance with ASTM D-3039 . Specimens were installed in a Baldwin Universal test machine using Zapel grips. A typical test set-up is shown in Figure 5.3-1. Extensometer clips were attached to the specimens using a 50.8mm (2.00 in.) gage length. Where applicable, strain gages were connected to x-y plotters. Thermocouples were installed at the center of each specimen and 50.8mm (2.0 in.) above and below the center to monitor temperature gradients. No thermocouples were used for the room temperature specimens. A strain rate of 8.3×10^{-5} m/m-sec (.005 in/in-min) was applied and controlled using a strain pacer connected to the test machine.

5.3.2 Test Results

Test results are summarized in Tables 5.3-1 through 5.3-4. Typical failed specimens, except moisture saturated, are shown in Figures 5.3-2 through 5.3-5.

Test results are plotted as functions of temperature and specimen conditioning in Figures 5.3-6 through 5.3-21. The $0^0{}_{16}$ laminates are fiber dominated and are not significantly affected by temperature (see Fig. 5.3-6, -7). As the laminate strengths become more resin dominated, $(0,\pm 45,90)_{4S}$, $\pm 45^0{}_{8S}$ and $90^0{}_{30}$, the property degradation with temperature becomes more significant. This trend is shown by the data in Figures 5.3-8 through 5.3-13.

Ultimate tensile stresses, in general, show a decline due to aging (Cond. 2) and thermal cycling (Cond. 3), except for the $\pm45^0{}_{8S}$ laminates. The $\pm45^0{}_{8S}$ laminate strength at room temperature is not affected by aging (Cond. 2) while there is a significant drop in strength due to thermal cycling (Cond. 3), (see Fig. 5.3-10). At elevated temperature, there is no significant change in the $\pm45_{8S}$ laminate strength due to aging or thermal cycling (see Fig. 5.3-11). This is because the $\pm45^0{}_{8S}$ laminate is resin matrix dominated and the resin strength degradation due to temperature is large compared to any strength degradation caused by aging or thermal cycling. In addition, the elevated temperature acts as a stress reliever to any locked in stresses caused by thermal cycling.

Tension modulus data are shown in Figures 5.3-14 through 5.3-21. As expected, fiber dominated laminates show no change due to increased temperature (see Fig. 5.3-14). As laminates become more matrix dominated, $(0,\pm45,90)_S$, ±45, and 90^0, the reduction in tension modulus due to temperature becomes greater (see Figs. 5.3-16 through 5.3-21). Aging and thermal cycling did not seem to have any significant effect on tension modulus (see Figs. 5.3-14 through 5.3-21).

The data indicate that moisture conditioning does not have any significant effect on tension strength and modulus when tested at room temperature; however, all the elevated temperature specimens had significant blistering of the laminate visible after test. This was caused by vaporization of the entrapped moisture and resulting internal pressure which resulted in separation of the lamina. The specimens were brought up to temperature in approximately 20 minutes and then held at temperature for 5 minutes prior to test. The blistering was most pronounced on the $(90)_{30}$ laminate and explains the low tension strength and modulus at 561^0K (550^0F) shown in Figure 5.3-13 and 5.3-21. Blistering of the $(0/\pm45/90)_{4S}$ laminate was less severe and, because the major portion of the load is carried by the 0^0 and 45^0 lamina, any strength degradation would be less pronounced (See Figures 5.3-9 and 5.3-17). The $(\pm45)_{8S}$ laminate also had blistering, however, the elevated temperature strength data was lost because of premature load pad failure. The modulus data are valid since they are based on strain gages.

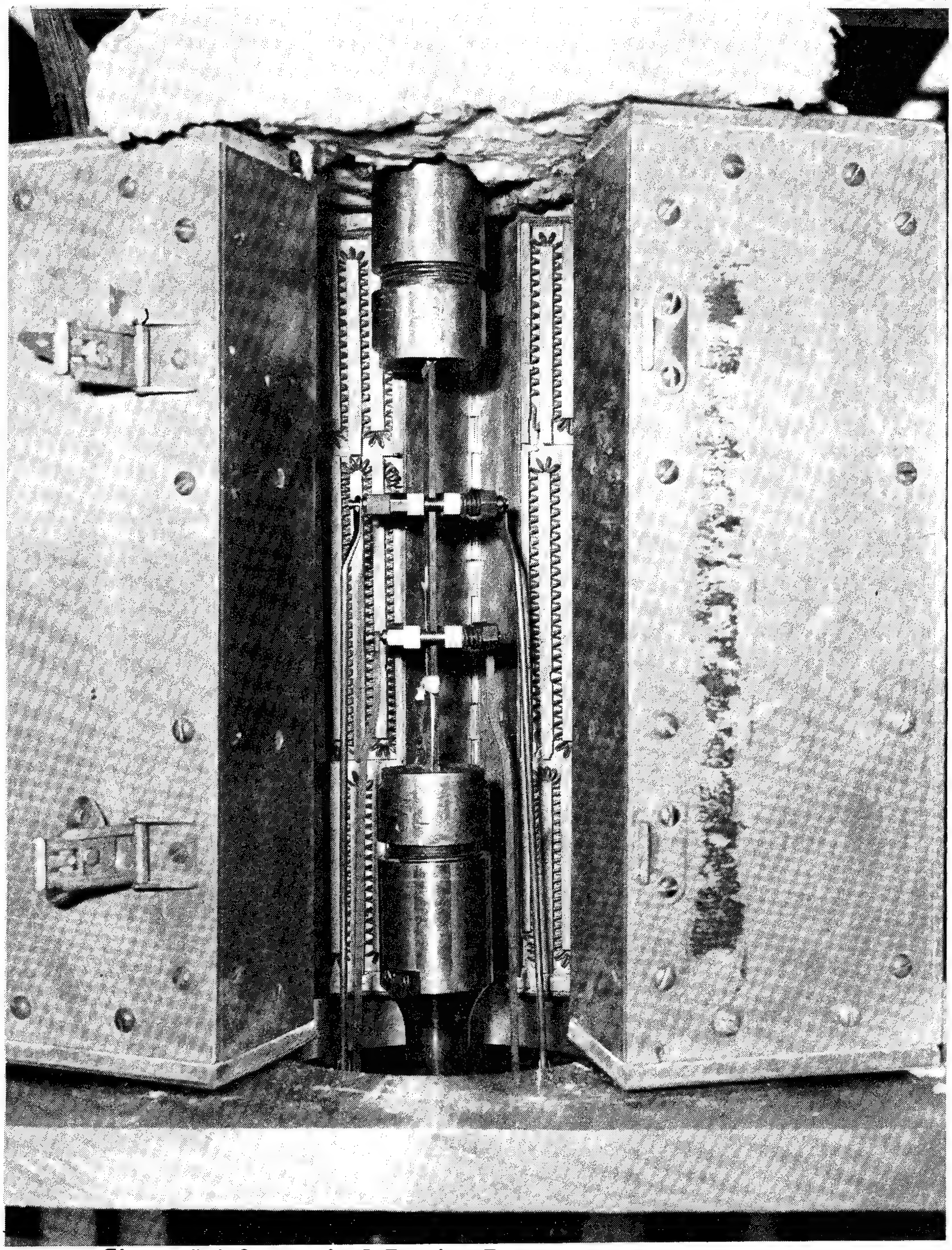


Figure 5.3-1: Typical Tension Test Setup
Celion 3000/PMR-15 Design Allowables

TABLE 5.3-1. CELION 3000/PMR-15 DESIGN ALLOWABLES TENSION TESTS [0]16 LAYUP

(a) SI UNITS

							Extensometer Data		Strain Gage Data	
COND. CODE	SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	FAILURE STRAIN	TENSION MODULUS GPA	TENSION MODULUS GPA	POISSON'S RATIO
1	4A-1	1.22	12.83	294.	19528.	1245.	.0110	118.2		
1	4A-2	1.17	12.95	294.	19328.	1269.	.0098	129.8		
1	4A-3	1.23	12.85	294.	20840.	1318.	.0110	120.7		
1	4A-4	1.20	12.81	561.	21174.	1373.	.0110	130.3		
1	4A-5	1.23	12.96	561.	20195.	1262.	.0098	117.3		
1	4A-6	1.24	12.65	561.	20017.	1271.	.0118	128.9		
2	4B-1	1.22	12.98	294.	19061.	1205.	.0092	120.9		
2	4B-2	1.09	12.93	294.	19617.	1388.	.0102	139.8		
2	4B-3	1.22	12.96	294.	20039.	1267.	.0100	127.9		
2	4B-7	1.12	12.88	561.	16636.	1151.	.0092	131.1		
2	4B-8	1.17	12.99	561.	16770.	1106.	.0078	135.1		
3	4C-1	1.16	12.86	294.	18438.	1242.	.0092	132.9		
3	4C-2	1.18	12.83	294.	18149.	1197.	.0098	130.7		
3	4C-3	1.17	12.80	294.	17748.	1191.	.0096	126.7		
3	4C-4	1.22	12.80	294.	20195.	1293.	.0095	118.7	131.	0.3103
3	4C-5	1.17	12.74	294.	18860.	1265.	.0106	123.6	128.	0.3441
3	4C-6	1.21	12.74	561.	19216.	1246.	.0096	126.0		
3	4C-7	1.18	12.71	561.	17909.	1189.	NO DATA	133.7		
3	4C-8	1.16	12.75	561.	17926.	1218.	.0104	125.6		
3	4C-9	1.18	12.65	561.	16903.	1129.	.0095	127.2	141.	0.3000
3	4C-10	1.15	12.72	561.	16948.	1157.	.0092	116.8	160.	0.5026

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA TENSION MODULUS MSI	STRAIN GAGE DATA TENSION MODULUS MSI	STRAIN GAGE DATA POISSON'S RATIO
1	4A-1	.0480	.5053	70.	4390.	180.6	.0110	17.15		
1	4A-2	.0462	.5100	70.	4345.	184.1	.0098	18.82		
1	4A-3	.0484	.5060	70.	4685.	191.2	.0110	17.50		
1	4A-4	.0473	.5045	550.	4760.	199.1	.0110	18.90		
1	4A-5	.0485	.5103	550.	4540.	183.0	.0098	17.01		
1	4A-6	.0490	.4980	550.	4500.	184.4	.0118	18.69		
2	4B-1	.0480	.5110	70.	4285.	174.8	.0092	17.53		
2	4B-2	.0430	.5091	70.	4410.	201.3	.0102	20.28		
2	4B-3	.0480	.5102	70.	4505.	183.8	.0100	18.55		
2	4B-7	.0441	.5069	550.	3740.	167.0	.0092	19.02		
2	4B-8	.0460	.5115	550.	3770.	160.4	.0078	19.59		
3	4C-1	.0455	.5063	70.	4145.	180.2	.0092	19.27		
3	4C-2	.0465	.5050	70.	4080.	173.6	.0098	18.96		
3	4C-3	.0459	.5040	70.	3990.	172.7	.0096	18.37		
3	4C-4	.0480	.5041	70.	4540.	187.6	.0095	17.22	19.0	0.3103
3	4C-5	.0460	.5015	70.	4240.	183.5	.0106	17.92	18.6	0.3441
3	4C-6	.0476	.5015	550.	4320.	180.7	.0096	18.27		
3	4C-7	.0465	.5002	550.	4026.	172.5	NO DATA	19.39		
3	4C-8	.0455	.5021	550.	4030.	176.7	.0104	18.22		
3	4C-9	.0465	.4982	550.	3800.	163.7	.0095	18.45	20.5	0.3000
3	4C-10	.0454	.5006	550.	3810.	167.8	.0092	16.94	23.2	0.5026

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-2. CELION 3000/PMR-15 DESIGN ALLOWABLES TENSION TESTS [90]30 LAYUP

(a) SI UNITS

							Extensometer Data		Strain Gage Data	
COND. CODE	SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	FAILURE STRAIN	TENSION MODULUS GPA	TENSION MODULUS GPA	POISSON'S RATIO
1	8A-1	2.37	25.60	294.	3336.	54.8	.0074	7.72		
1	8A-2	2.32	25.58	294.	3043.	51.2	.0063	8.48		
1	8A-3	2.37	25.61	294.	2135.	35.1	.0044	8.34		
1	8A-4	2.16	25.35	561.	970.	17.7	.0030	6.00		
1	8A-5	2.14	25.49	561.	1246.	22.8	.0044	5.58		
1	8A-6	2.16	25.58	561.	1076.	19.4	.0034	5.58		
2	8B-1	2.31	25.48	294.	2535.	43.1	.0054	8.14		
2	8B-2	2.37	25.48	294.	3043.	50.3	.0064	8.48		
2	8B-3	2.36	25.55	294.	2580.	42.7	.0052	8.48		
2	8B-4	2.34	25.63	561.	1165.	19.3	.0036	5.65		
2	8B-5	2.39	25.50	561.	1112.	18.3	.0037	4.96		
2	8B-6	2.34	25.70	561.	970.	16.1	.0028	6.21		
3	9B-1	2.29	25.43	294.	2616.	45.0	.0061	7.65		
3	9B-2	2.34	25.34	294.	2531.	42.5	.0056	7.45		
3	9B-3	2.34	25.48	294.	2447.	40.9	.0054	7.79		
3	9B-4	2.29	25.37	294.	2046.	35.2	.0046	8.00	8.76	0.0323
3	9B-5	2.30	25.43	294.	2589.	44.3	.0059	8.14	8.48	0.0316
3	9B-6	2.30	25.50	561.	716.	12.2	.0023	5.86		
3	9B-7	2.32	25.50	561.	1076.	18.1	.0043	4.90		
3	9B-8	2.32	25.49	561.	649.	11.0	.0025	4.41		
3	9B-9	2.27	25.68	561.	1277.	21.9	.0041	6.48	6.29	0.0165
3	9B-10	2.26	25.68	561.	1152.	19.8	.0040	5.38	6.14	0.0187
4	1-2-4-1	2.36	25.46	294.	2398.	39.9	.0050	7.31		
4	1-2-4-2	2.34	25.43	294.	2691.	45.3	.0052	7.38		
4	1-2-4-3	2.36	25.46	294.	2611.	43.4	.0058	7.31		
4	1-2-4-4	2.34	25.45	561.	445.	7.4	NO DATA	2.34		
4	1-2-4-5	2.36	25.50	561.	436.	7.2	NO DATA	2.93		
4	1-2-4-6	2.41	25.44	561.	507.	8.3	.0026	2.87		

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-2. CONCLUDED

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA TENSION MODULUS MSI	STRAIN GAGE DATA TENSION MODULUS MSI	STRAIN GAGE DATA POISSON'S RATIO
1	8A-1	.0934	1.0080	70.	750.	7.950	.0074	1.12		
1	8A-2	.0915	1.0070	70.	684.	7.420	.0063	1.23		
1	8A-3	.0934	1.0083	70.	480.	5.090	.0044	1.21		
1	8A-4	.0850	0.9980	550.	218.	2.570	.0030	0.87		
1	8A-5	.0841	1.0036	550.	280.	3.310	.0044	0.81		
1	8A-6	.0850	1.0070	550.	242.	2.820	.0034	0.81		
2	8B-1	.0908	1.0033	70.	570.	6.250	.0054	1.18		
2	8B-2	.0935	1.0030	70.	684.	7.290	.0064	1.23		
2	8B-3	.0928	1.0060	70.	580.	6.200	.0052	1.23		
2	8B-4	.0923	1.0092	550.	262.	2.800	.0036	0.82		
2	8B-5	.0940	1.0039	550.	250.	2.650	.0037	0.72		
2	8B-6	.0922	1.0120	550.	218.	2.330	.0028	0.90		
3	9B-1	.0900	1.0011	70.	588.	6.520	.0061	1.11		
3	9B-2	.0923	0.9978	70.	569.	6.170	.0056	1.08		
3	9B-3	.0923	1.0030	70.	550.	5.930	.0054	1.13		
3	9B-4	.0900	0.9989	70.	460.	5.110	.0046	1.16	1.27	0.0323
3	9B-5	.0904	1.0011	70.	582.	6.430	.0059	1.18	1.23	0.0316
3	9B-6	.0904	1.0040	550.	161.	1.770	.0023	0.85		
3	9B-7	.0915	1.0039	550.	242.	2.630	.0043	0.71		
3	9B-8	.0912	1.0034	550.	146.	1.600	.0025	0.64		
3	9B-9	.0892	1.0111	550.	287.	3.180	.0041	0.94	0.91	0.0165
3	9B-10	.0890	1.0109	550.	259.	2.870	.0040	0.78	0.89	0.0187
4	1-2-4-1	.0930	1.0022	70.	539.	5.783	.0050	1.06		
4	1-2-4-2	.0920	1.0013	70.	605.	6.569	.0052	1.07		
4	1-2-4-3	.0930	1.0025	70.	587.	6.298	.0058	1.06		
4	1-2-4-4	.0920	1.0021	550.	100.	1.079	NO DATA	0.34		
4	1-2-4-5	.0930	1.0039	550.	98.	1.044	NO DATA	0.43		
4	1-2-4-6	.0950	1.0015	550.	114.	1.204	.0026	0.42		

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-3. CELION 3000/PMR-15 DESIGN ALLOWABLES TENSION TESTS [0/+-45/90]4S LAYUP

(a) SI UNITS

							Extensometer Data		Strain Gage Data	
COND. CODE	SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	FAILURE STRAIN	TENSION MODULUS GPA	TENSION MODULUS GPA	POISSON'S RATIO
1	14A-1	2.35	25.702	294.	30871.	510.	.0103	50.7		
1	14A-2	2.45	25.718	294.	31049.	493.	NO DATA	49.8		
1	14A-3	2.33	25.486	294.	31093.	523.	.0112	46.9		
1	14A-4	2.41	25.707	561.	31582.	509.	NO DATA	44.2		
1	14A-5	2.46	25.705	561.	31138.	491.	.0112	44.2		
1	14A-7	2.44	25.707	561.	27935.	445.	.0111	45.0		
2	14B-1	2.42	25.634	294.	29091.	468.	.0098	49.1		
2	14B-2	2.31	25.695	294.	29002.	489.	NO DATA	51.2		
2	14B-3	2.39	25.679	294.	29180.	475.	.0096	50.1		
2	14B-4	2.45	25.748	561.	29180.	463.	.0101	47.1		
2	14B-5	2.41	25.664	561.	27134.	438.	.0107	41.0		
2	14B-6	2.36	25.705	561.	27579.	455.	.0096	49.4		
3	15B-1	2.51	25.573	294.	24065.	374.	.0088	47.0		
3	15B-2	2.51	25.603	294.	25844.	402.	.0101	46.7		
3	15B-3	2.50	25.527	294.	26689.	417.	.0097	45.8		
3	15B-4	2.50	25.555	294.	25577.	400.	.0104	42.1	45.0	.3152
3	15B-5	2.52	25.532	294.	26378.	410.	.0100	44.3	47.9	.3407
3	15B-6	2.51	25.453	561.	25355.	396.	.0087	53.3		
3	15B-7	2.50	25.436	561.	20417.	TAB FAILURE	NO DATA	45.5		
3	15B-8	2.49	25.585	561.	25043.	392.	.0097	40.9		
3	15B-9	2.50	25.596	561.	22508.	351.	.0078	43.0	47.5	.3425
3	15B-10	2.51	25.522	561.	23442.	365.	.0100	46.0	48.0	.3529
4	1-3-4-1	2.57	25.710	561.	25088.	381.	.0099	39.1		
4	1-3-4-2	2.57	25.679	561.	25177.	382.	.0096	39.8		
4	1-3-4-3	2.59	25.735	561.	22775.	342.	.0087	39.7		
4	1-3-4-4	2.57	25.725	561.	25177.	381.	.0095	39.6		
4	1-3-4-5	2.59	25.748	561.	24421.	366.	.0095	39.0		

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-3. CONCLUDED

(b) U.S. CUSTOMARY UNITS

							EXTENSOMETER DATA		STRAIN GAGE DATA	
COND. CODE	SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	FAILURE STRAIN	TENSION MODULUS MSI	TENSION MODULUS MSI	POISSON'S RATIO
1	14A-1	.0926	1.0119	70.	6940.	74.0	.0103	7.36		
1	14A-2	.0963	1.0125	70.	6980.	71.5	NO DATA	7.22		
1	14A-3	.0919	1.0034	70.	6990.	75.8	.0112	6.80		
1	14A-4	.0950	1.0121	550.	7100.	73.8	NO DATA	6.41		
1	14A-5	.0970	1.0120	550.	7000.	71.2	.0112	6.41		
1	14A-7	.0960	1.0121	550.	6280.	64.6	.0111	6.52		
2	14B-1	.0953	1.0092	70.	6540.	67.9	.0098	7.12		
2	14B-2	.0908	1.0116	70.	6520.	70.9	NO DATA	7.43		
2	14B-3	.0942	1.0110	70.	6560.	68.9	.0096	7.27		
2	14B-4	.0963	1.0137	550.	6560.	67.2	.0101	6.83		
2	14B-5	.0950	1.0104	550.	6100.	63.5	.0107	5.94		
2	14B-6	.0928	1.0120	550.	6200.	66.0	.0096	7.16		
3	15B-1	.0990	1.0068	70.	5410.	54.2	.0088	6.82		
3	15B-2	.0988	1.0080	70.	5810.	58.3	.0101	6.78		
3	15B-3	.0986	1.0050	70.	6000.	60.5	.0097	6.64		
3	15B-4	.0985	1.0061	70.	5750.	58.0	.0104	6.11	6.52	.3152
3	15B-5	.0991	1.0052	70.	5930.	59.5	.0100	6.42	6.95	.3407
3	15B-6	.0990	1.0021	550.	5700.	57.4	.0087	7.73		
3	15B-7	.0983	1.0014	550.	4590.	TAB FAILURE	NO DATA	6.60		
3	15B-8	.0981	1.0073	550.	5630.	56.9	.0097	5.93		
3	15B-9	.0986	1.0077	550.	5060.	50.9	.0079	6.23	6.89	.3425
3	15B-10	.0990	1.0048	550.	5270.	52.9	.0100	6.67	6.96	.3529
4	1-3-4-1	.1010	1.0122	550.	5640.	55.2	.0099	5.67		
4	1-3-4-2	.1010	1.0110	550.	5660.	55.4	.0096	5.77		
4	1-3-4-3	.1020	1.0132	550.	5120.	49.6	.0087	5.76		
4	1-3-4-4	.1010	1.0128	550.	5660.	55.3	.0095	5.75		
4	1-3-4-5	.1020	1.0137	550.	5490.	53.1	.0095	5.65		

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-4. CELION 3000/PMR-15 DESIGN ALLOWABLES TENSION TESTS [+-45]8S LAYUP

(a) SI UNITS

COND. CODE	SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA TENSION MODULUS GPA	STRAIN GAGE DATA TENSION MODULUS GPA	STRAIN GAGE DATA POISSON'S RATIO
1	10A-1	2.55	25.733	294.	13011.	198.	NO DATA	14.3		
1	10A-2	2.55	25.697	294.	13634.	208.	NO DATA	15.0		
1	10A-3	2.57	25.756	294.	13367.	202.	NO DATA	14.2		
1	10A-4	2.55	25.705	561.	6672.	101.	.0430	6.8		
1	10A-5	2.57	25.748	561.	7348.	111.	NO DATA	9.1		
2	10B-1	2.45	25.700	294.	12277.	194.	NO DATA	14.4		
2	10B-2	2.50	25.758	294.	13278.	205.	NO DATA	14.1		
2	10B-3	2.45	25.730	294.	13656.	216.	NO DATA	14.9		
2	10B-4	2.49	25.730	294.	13300.	207.	NO DATA	14.5	16.5	.8690
2	10B-5	2.50	25.679	561.	6236.	97.	NO DATA	9.7		
2	10B-6	2.51	25.773	561.	6041.	93.	NO DATA	9.3		
2	10B-7	2.46	25.756	561.	7384.	116.	NO DATA	8.1		
2	10B-8	2.41	25.629	561.	5987.	97.	NO DATA	10.2	10.1	.8139
3	11B-1	2.48	25.700	294.	8096.	127.	.0172	12.5		
3	11B-2	2.48	25.664	294.	9519.	150.	NO DATA	13.7		
3	11B-3	2.48	25.502	294.	9942.	157.	NO DATA	13.4		
3	11B-4	2.44	25.748	294.	10898.	173.	NO DATA	13.0	14.9	.8253
3	11B-5	2.48	25.522	294.	9341.	147.	NO DATA	12.6	14.3	.7449
3	11B-6	2.50	25.603	561.	6557.	102.	NO DATA	8.8		
3	11B-7	2.41	25.692	561.	6984.	112.	NO DATA	9.5		
3	11B-8	2.46	25.629	561.	7509.	119.	NO DATA	10.5		
3	11B-9	2.49	25.679	561.	7215.	112.	NO DATA	10.1		
3	11B-10	2.40	25.776	561.	6646.	107.	NO DATA	7.7		
4	1-6-4-1	2.59	25.613	294.	15947.	241.	NO DATA	19.0	15.7	.7581
4	1-6-4-2	2.59	25.583	294.	16014.	242.	NO DATA	16.7	15.2	.8364
4	1-6-4-3	2.46	25.702	294.	12566.	199.	NO DATA	14.3	15.9	.7909
4	1-6-4-4	2.59	25.705	561.	6895.	TAB FAILURE	NO DATA	7.2		
4	1-6-4-5	2.59	25.702	561.	6072.	TAB FAILURE	NO DATA	8.9		
4	1-6-4-6	2.54	25.712	561.	5405.	TAB FAILURE	NO DATA	8.1		

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.3-4. CONCLUDED

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA TENSION MODULUS MSI	STRAIN GAGE DATA TENSION MODULUS MSI	STRAIN GAGE DATA POISSON'S RATIO
1	10A-1	.1003	1.0131	70.	2925.	28.7	NO DATA	2.08		
1	10A-2	.1005	1.0117	70.	3065.	30.1	NO DATA	2.18		
1	10A-3	.1011	1.0140	70.	3005.	29.3	NO DATA	2.06		
1	10A-4	.1005	1.0120	550.	1500.	14.7	.0430	0.99		
1	10A-5	.1010	1.0137	550.	1652.	16.1	NO DATA	1.32		
2	10B-1	.0965	1.0118	70.	2760.	28.2	NO DATA	2.09		
2	10B-2	.0985	1.0141	70.	2985.	29.8	NO DATA	2.05		
2	10B-3	.0966	1.0130	70.	3070.	31.3	NO DATA	2.16		
2	10B-4	.0981	1.0130	70.	2990.	30.0	NO DATA	2.10	2.40	.8690
2	10B-5	.0984	1.0110	550.	1402.	14.0	NO DATA	1.40		
2	10B-6	.0990	1.0147	550.	1358.	13.5	NO DATA	1.35		
2	10B-7	.0969	1.0140	550.	1660.	16.8	NO DATA	1.18		
2	10B-8	.0950	1.0090	550.	1346.	14.0	NO DATA	1.48	1.46	.8139
3	11B-1	.0975	1.0118	70.	1820.	18.4	.0172	1.81		
3	11B-2	.0975	1.0104	70.	2140.	21.7	NO DATA	1.99		
3	11B-3	.0977	1.0040	70.	2235.	22.7	NO DATA	1.95		
3	11B-4	.0960	1.0137	70.	2450.	25.1	NO DATA	1.89	2.16	.8253
3	11B-5	.0977	1.0048	70.	2100.	21.3	NO DATA	1.83	2.08	.7449
3	11B-6	.0984	1.0080	550.	1474.	14.8	NO DATA	1.27		
3	11B-7	.0948	1.0115	550.	1570.	16.3	NO DATA	1.38		
3	11B-8	.0970	1.0090	550.	1688.	17.2	NO DATA	1.53		
3	11B-9	.0980	1.0110	550.	1622.	16.3	NO DATA	1.46		
3	11B-10	.0944	1.0148	550.	1494.	15.5	NO DATA	1.12		
4	1-6-4-1	.1020	1.0084	70.	3585.	35.0	NO DATA	2.75	2.27	.7581
4	1-6-4-2	.1020	1.0072	70.	3600.	35.1	NO DATA	2.42	2.21	.8364
4	1-6-4-3	.0970	1.0119	70.	2825.	28.8	NO DATA	2.07	2.31	.7909
4	1-6-4-4	.1020	1.0120	550.	1550.	TAB FAILURE	NO DATA	1.04		
4	1-6-4-5	.1020	1.0119	550.	1365.	TAB FAILURE	NO DATA	1.29		
4	1-6-4-6	.1000	1.0123	550.	1215.	TAB FAILURE	NO DATA	1.18		

NOTE: FIBER VOLUME = 51.4 %

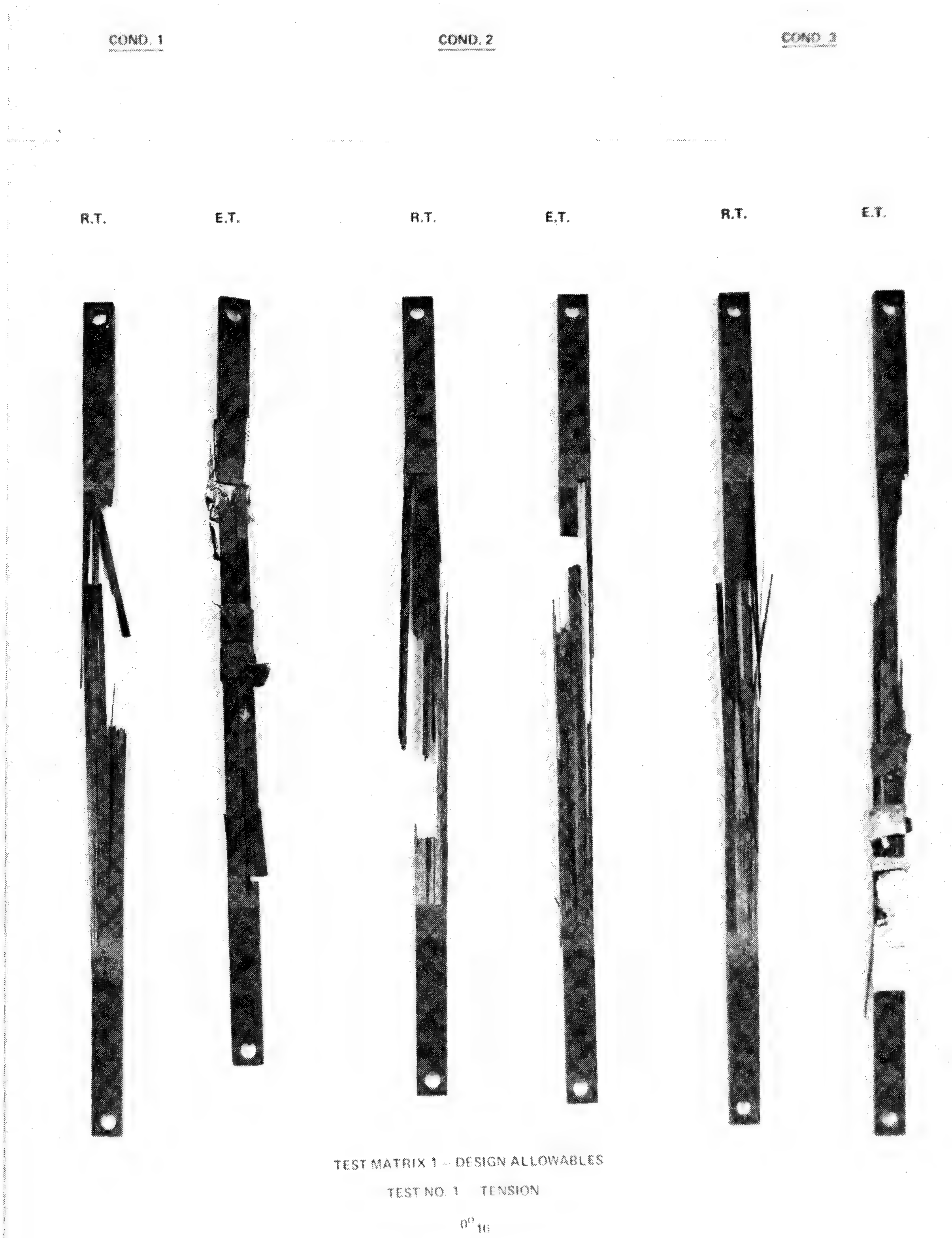


Figure 5.3-2: Celion 3000/PMR-15 Design Allowables Tension Tests
$0^{\circ}{}_{16}$ Layup - Failed Specimens

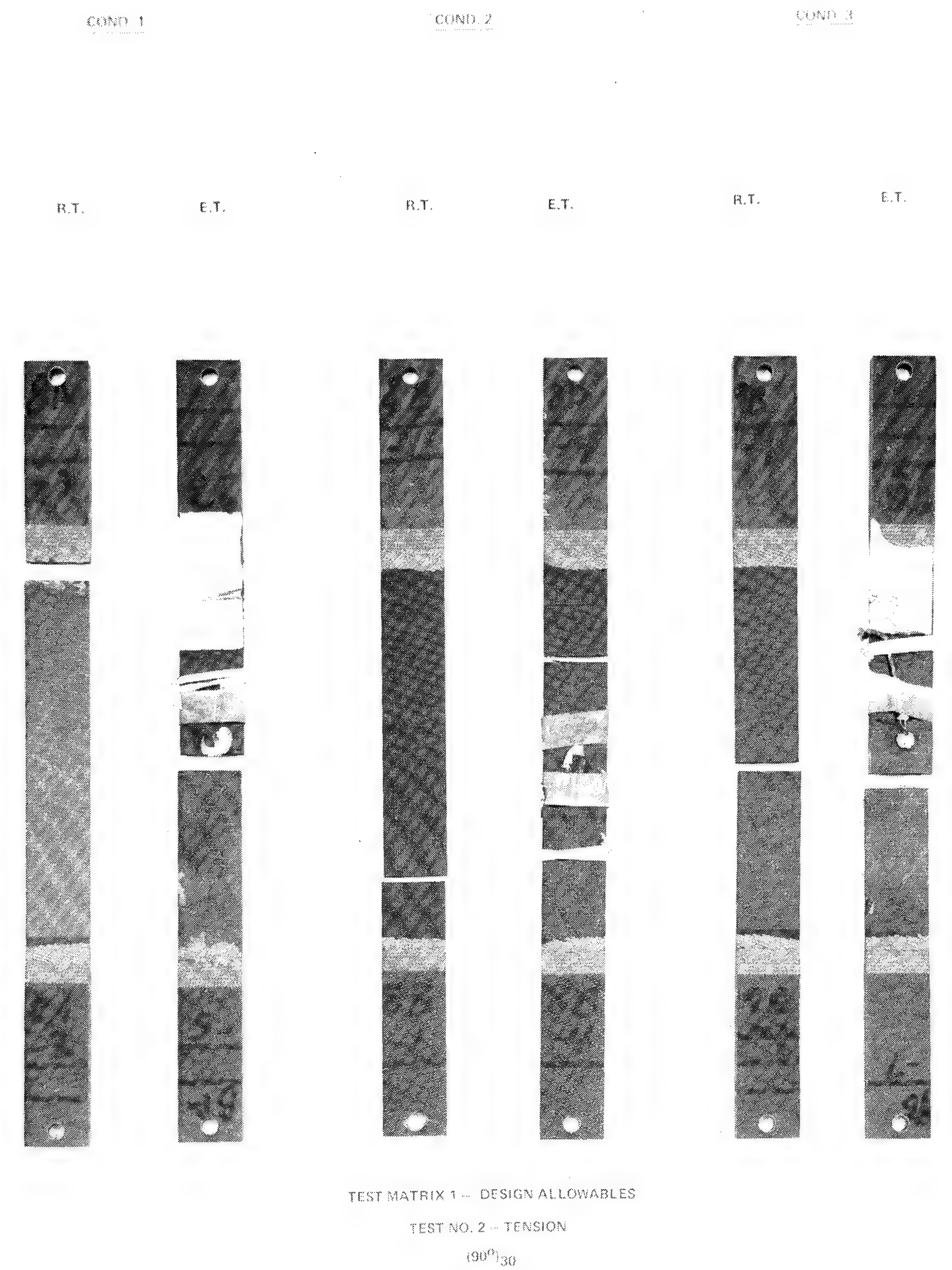


Figure 5.3-3: Celion 3000/PMR-15 Design Allowables Tension Tests $[90°]_{30}$ Layup - Failed Specimens

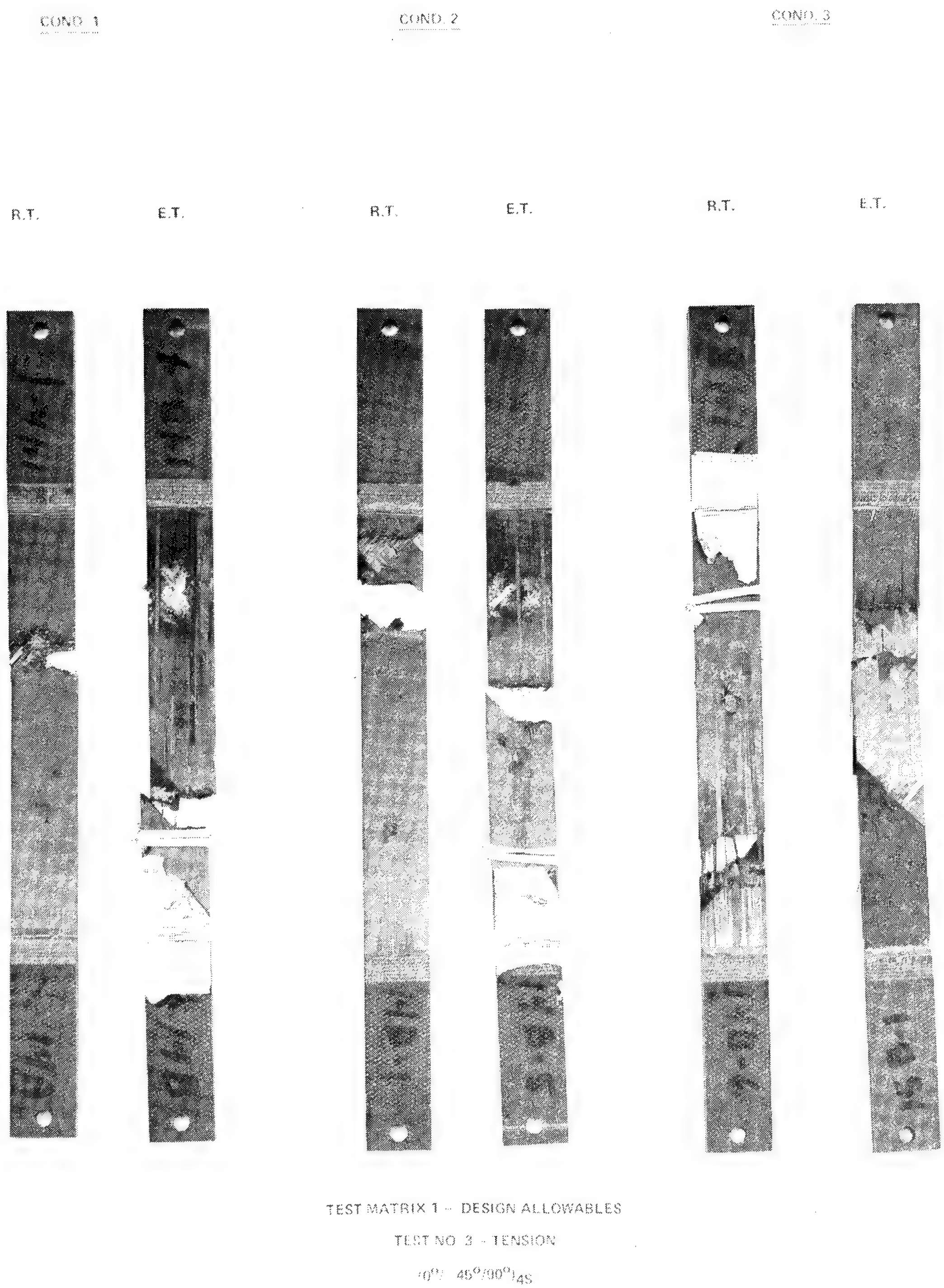


Figure 5.3-4: Celion 3000/PMR-15 Design Allowables Tension Tests $(0/\underline{+}45/90)_{4S}$ Layup - Failed Specimens

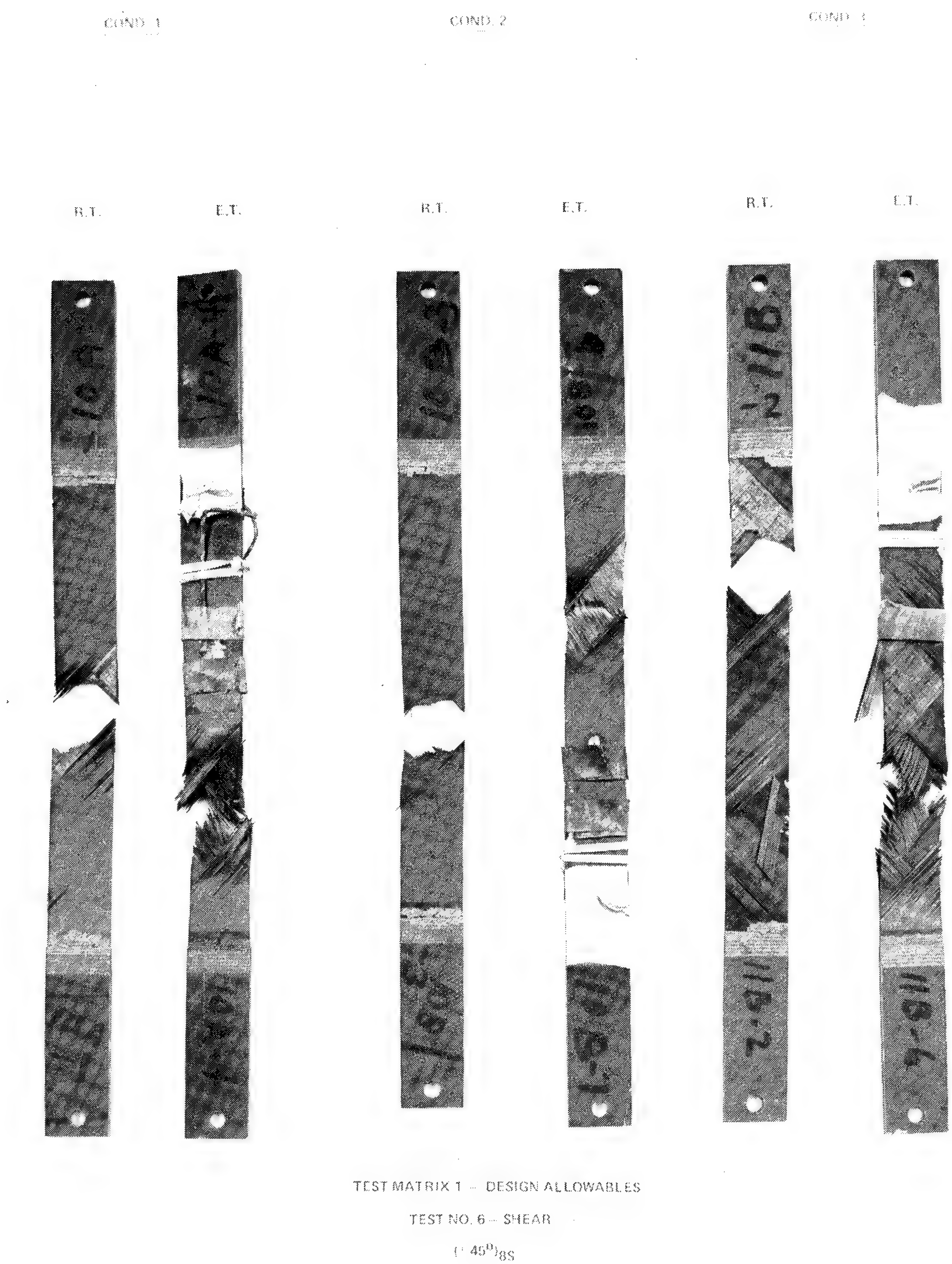


Figure 5.3-5: Celion 3000/PMR-15 Design Allowables Tension Tests $(\pm 45)_{8S}$ Layup - Failed Specimens

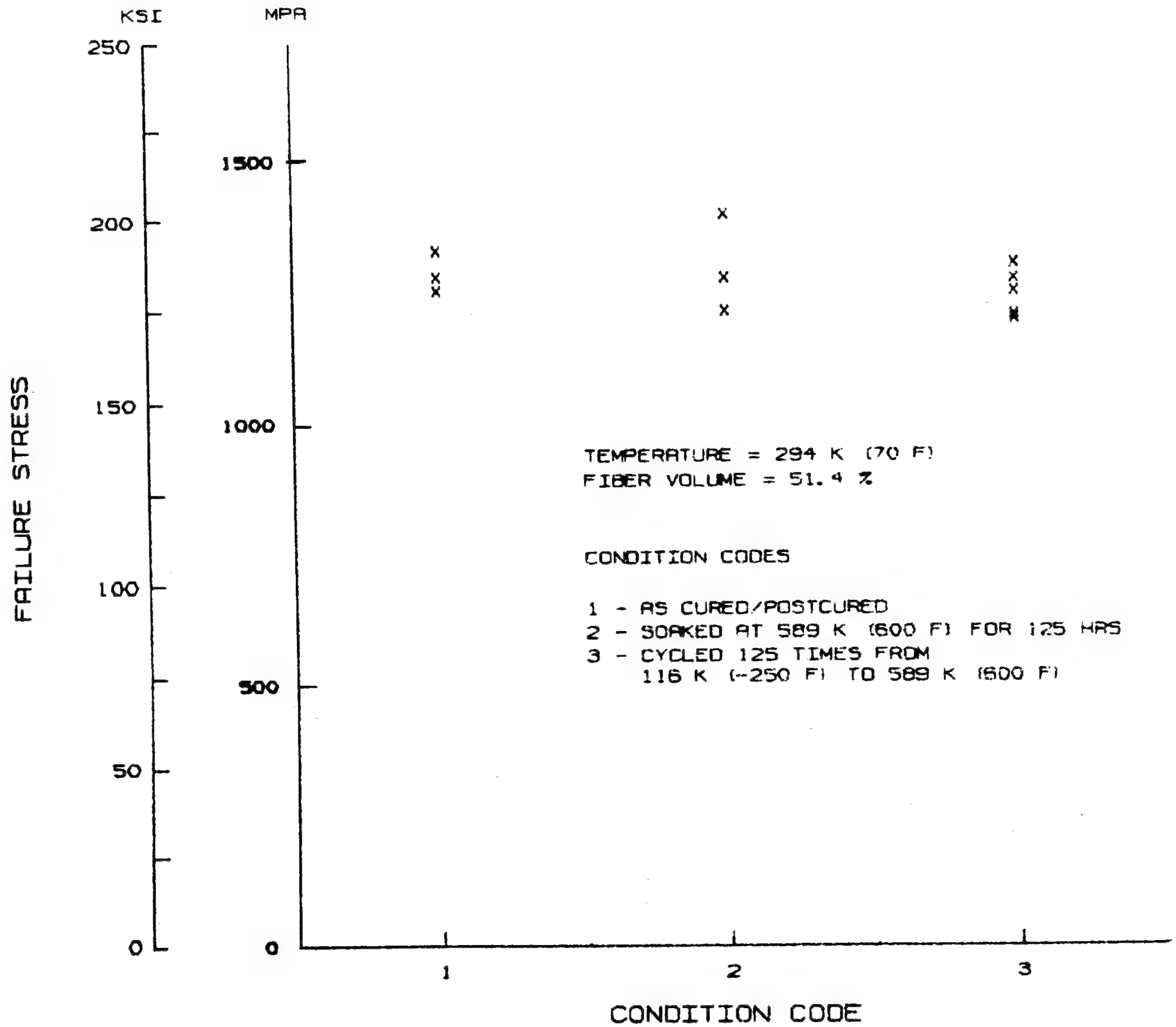


Figure 5.3-6: Celion 3000/PMR-15 Tension Tests $(0)_{16}$ Layup 294K (70^{0}) - Failure Stress

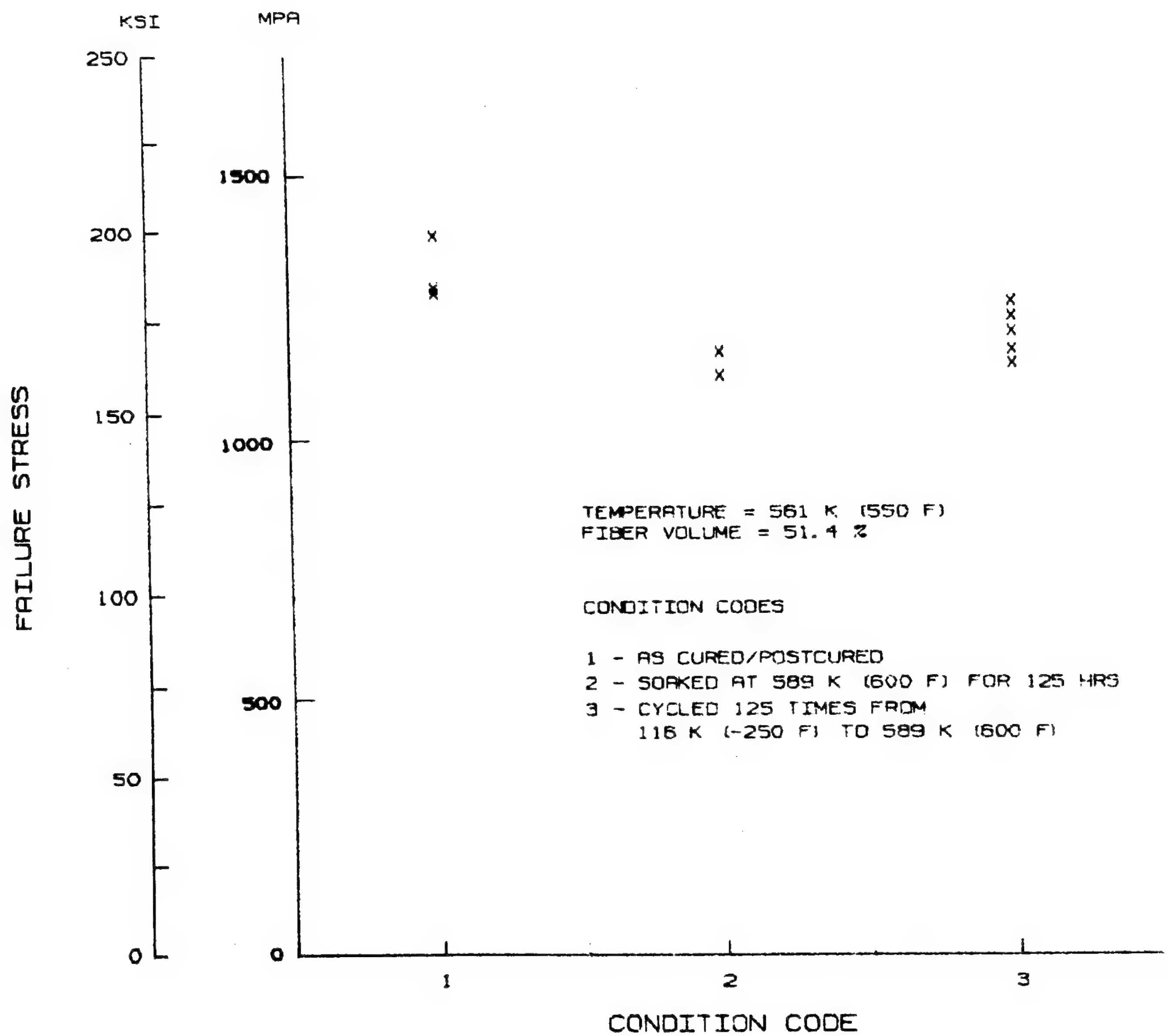


Figure 5.3-7: Celion 3000/PMR-15 Tension Tests $(0)_{16}$ Layup 561K (550^{0}F) - Failure Stress

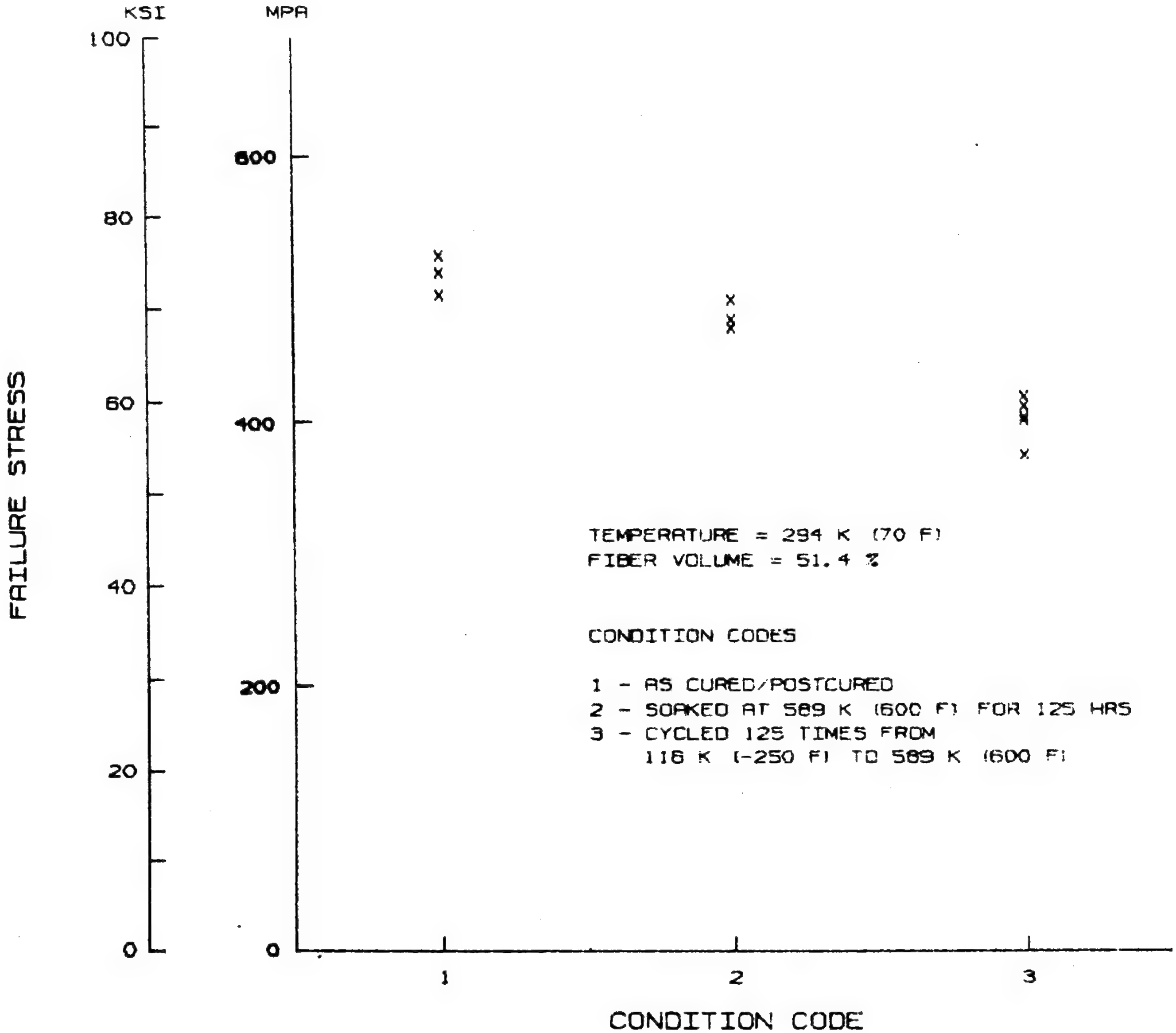


Figure 5.3-8: Celion 3000/PMR-15 Tension Tests $(0/+45/90)_{4S}$ Layup 294K (70^{o}F) - Failure Stress

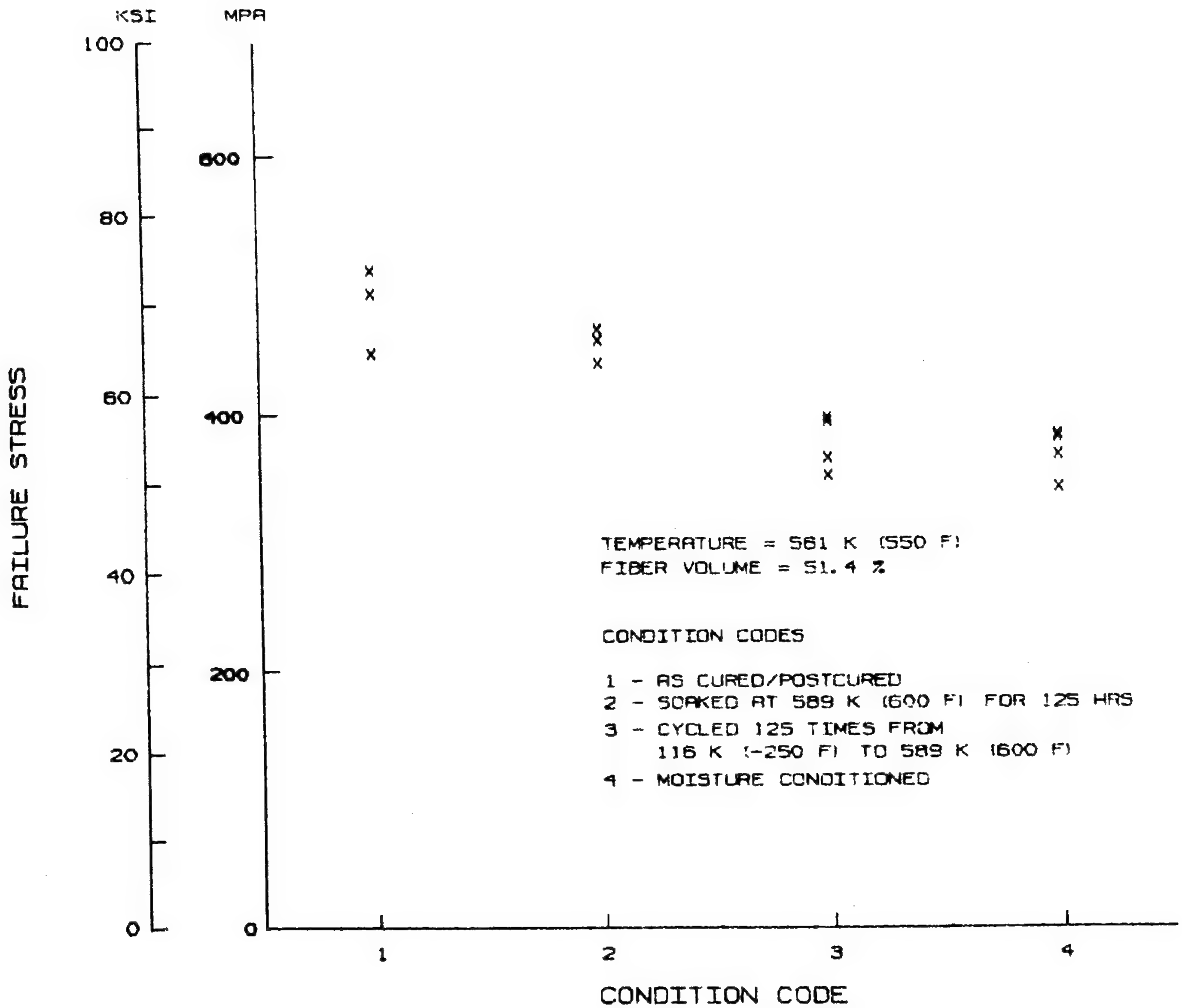


Figure 5.3-9: Celion 3000/PMR-15 Tension Tests $(0/+45/90)_{4S}$ Layup 561K (550^{0}F) - Failure Stress

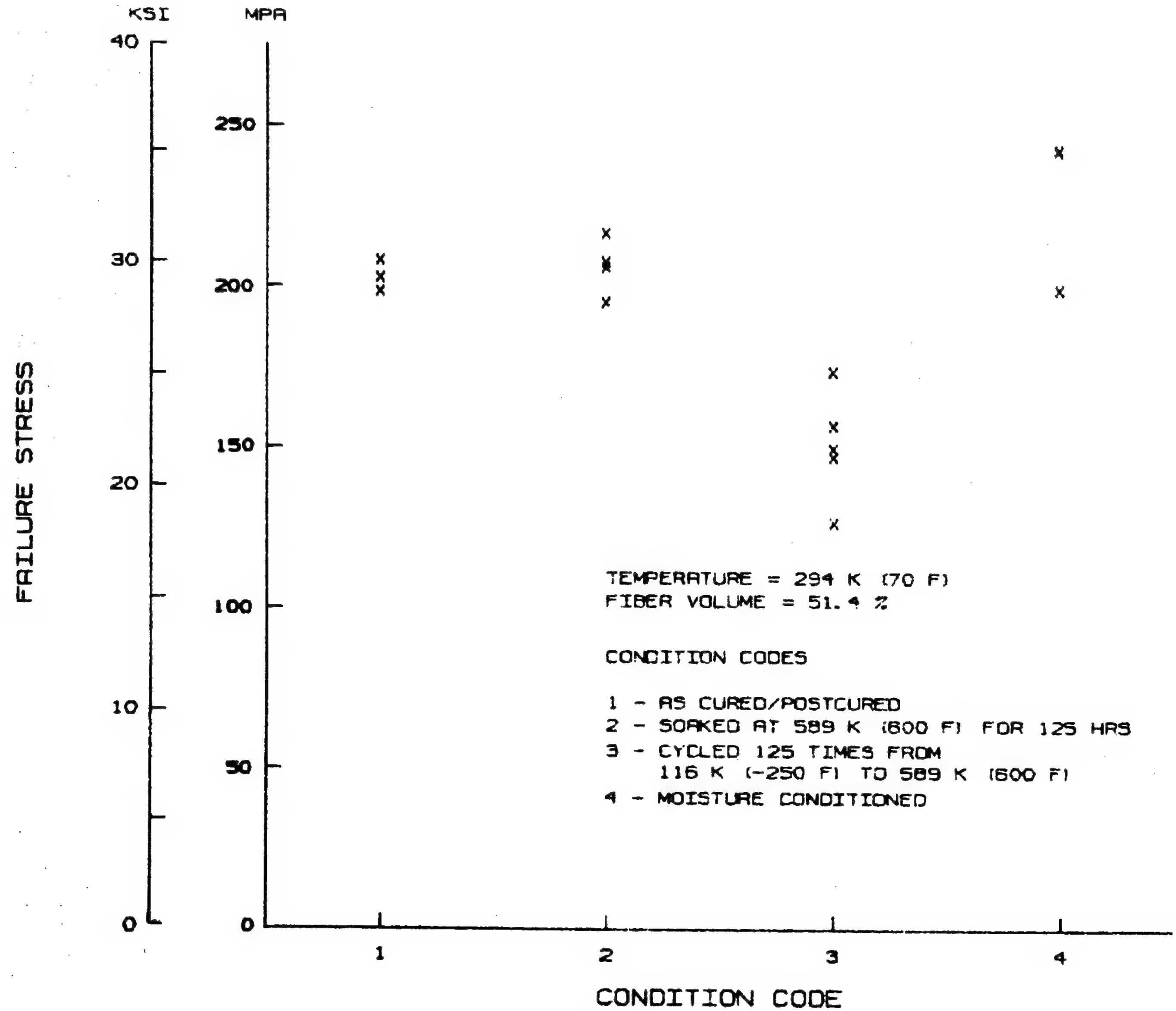


Figure 5.3-10: Celion 3000/PMR-15 Tension Tests $(+45)_{8S}$ Layup 294K (70^{o}F) - Failure Stress

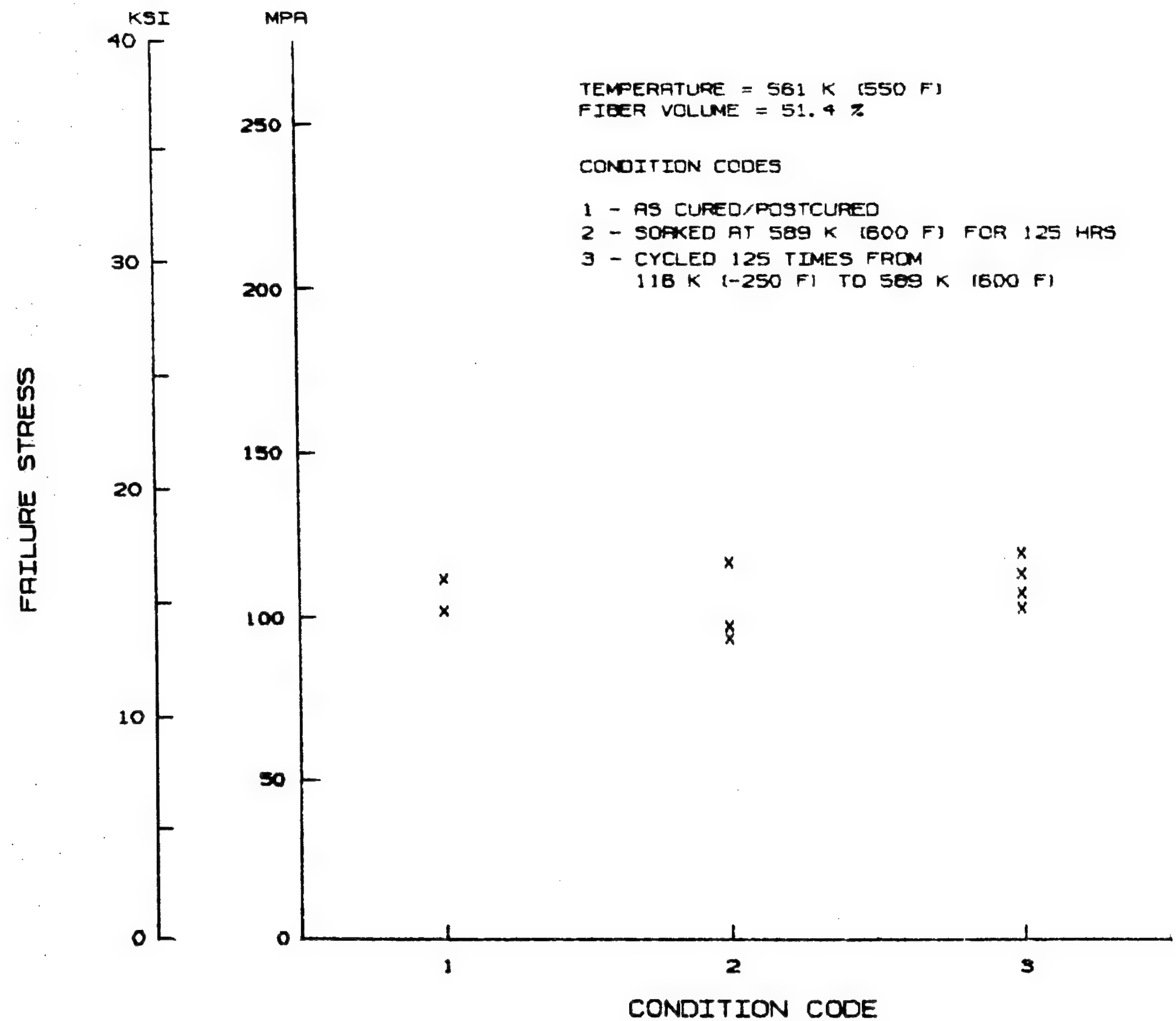


Figure 5.3-11: Celion 3000/PMR-15 Tension Tests $(+45)_{8S}$ Layup 561K (550^{0}F) - Failure Stress

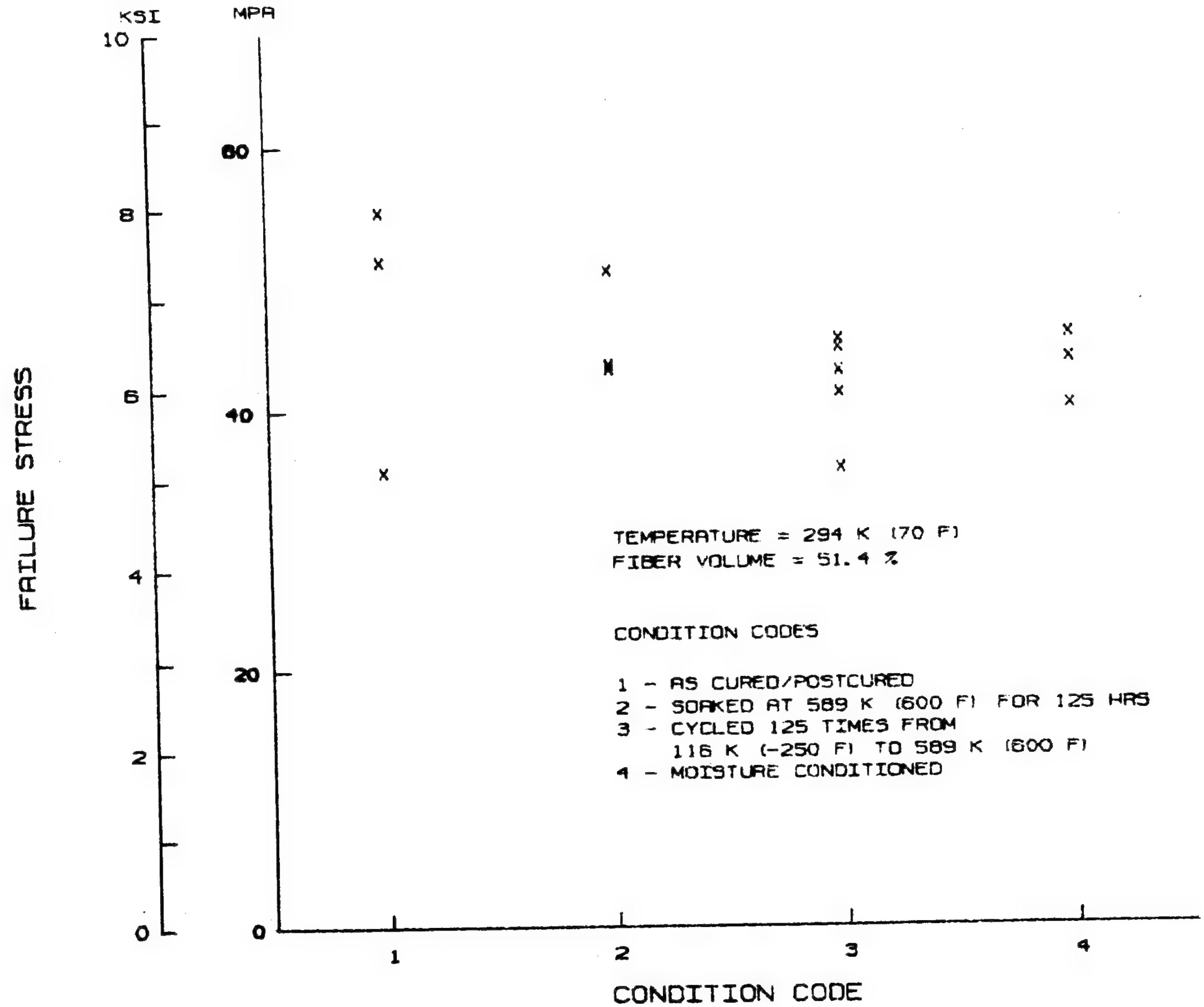


Figure 5.3-12: Celion 3000/PMR-15 Tension Tests $(90)_{30}$ Layup 294K (70^{0}F) - Failure Stress

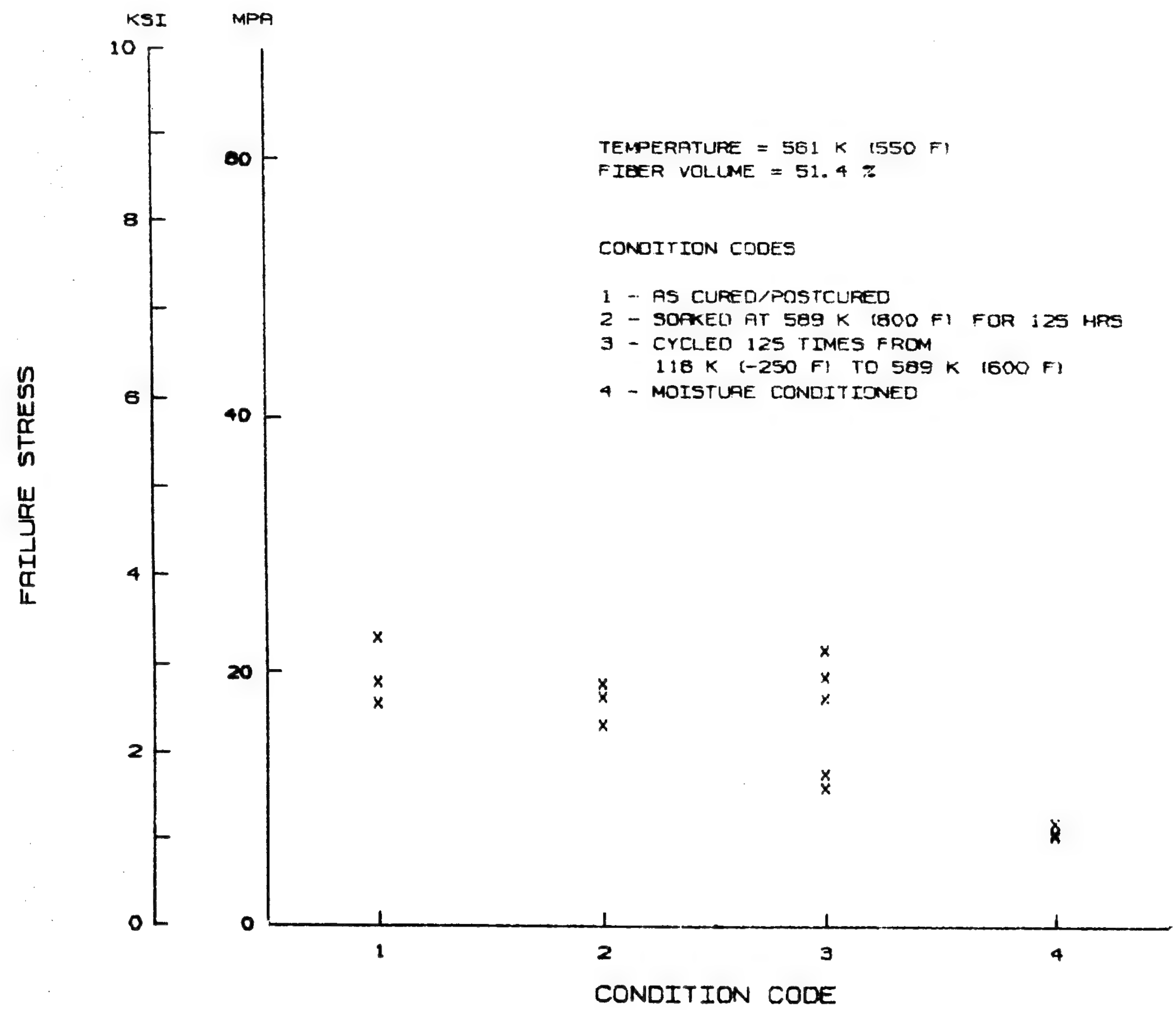


Figure 5.3-13: Celion 3000/PMR-15 Tension Tests $(90)_{30}$ Layup 561K (550^{O}F) - Failure Stress

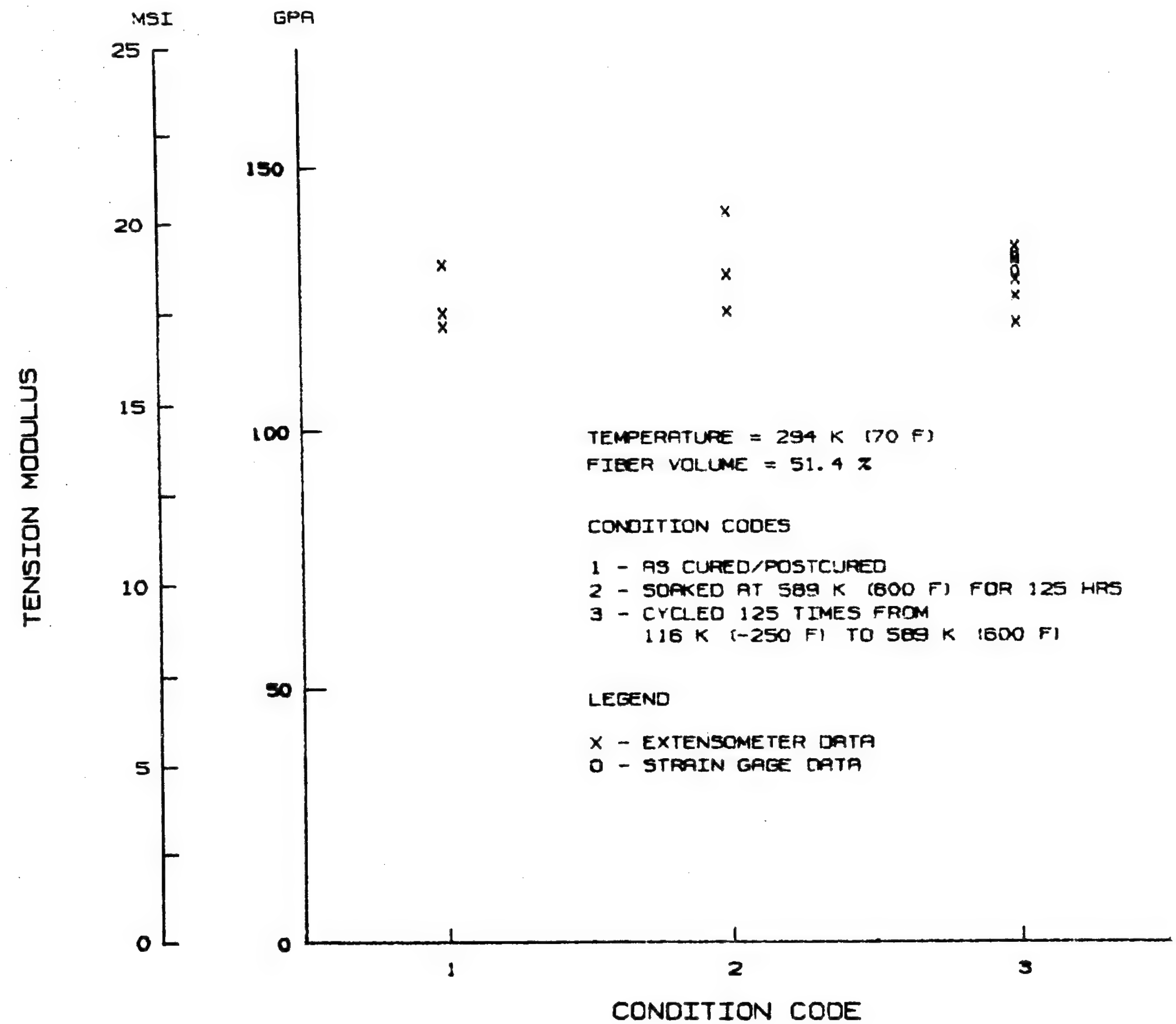


Figure 5.3-14: Celion 3000/PMR-15 Tension Tests $(0)_{16}$ Layup 294K (70^{o}F) - Modulus

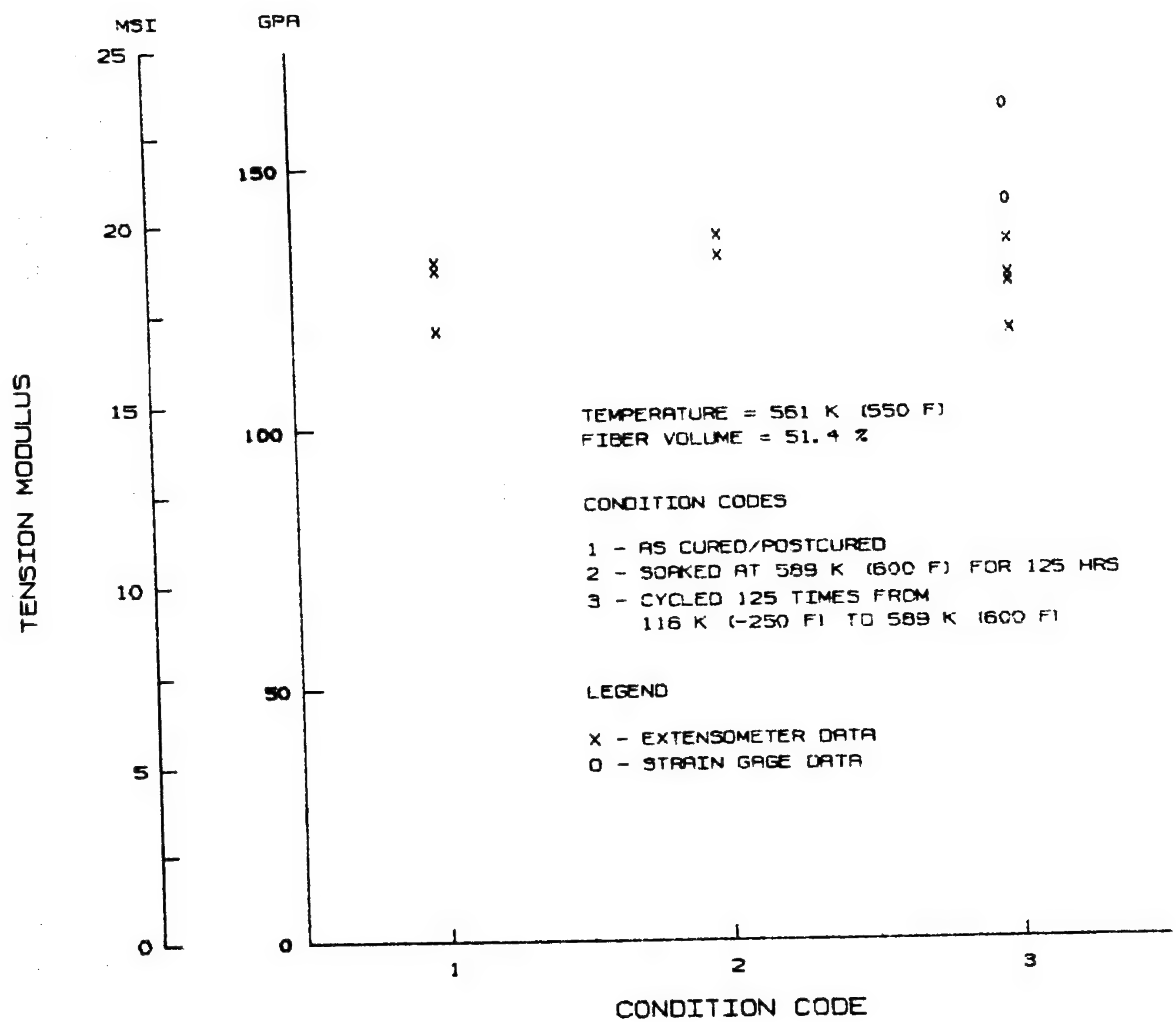


Figure 5.3-15: Celion 3000/PMR-15 Tension Tests $(0)_{16}$ Layup 561K (550^{0}F) - Modulus

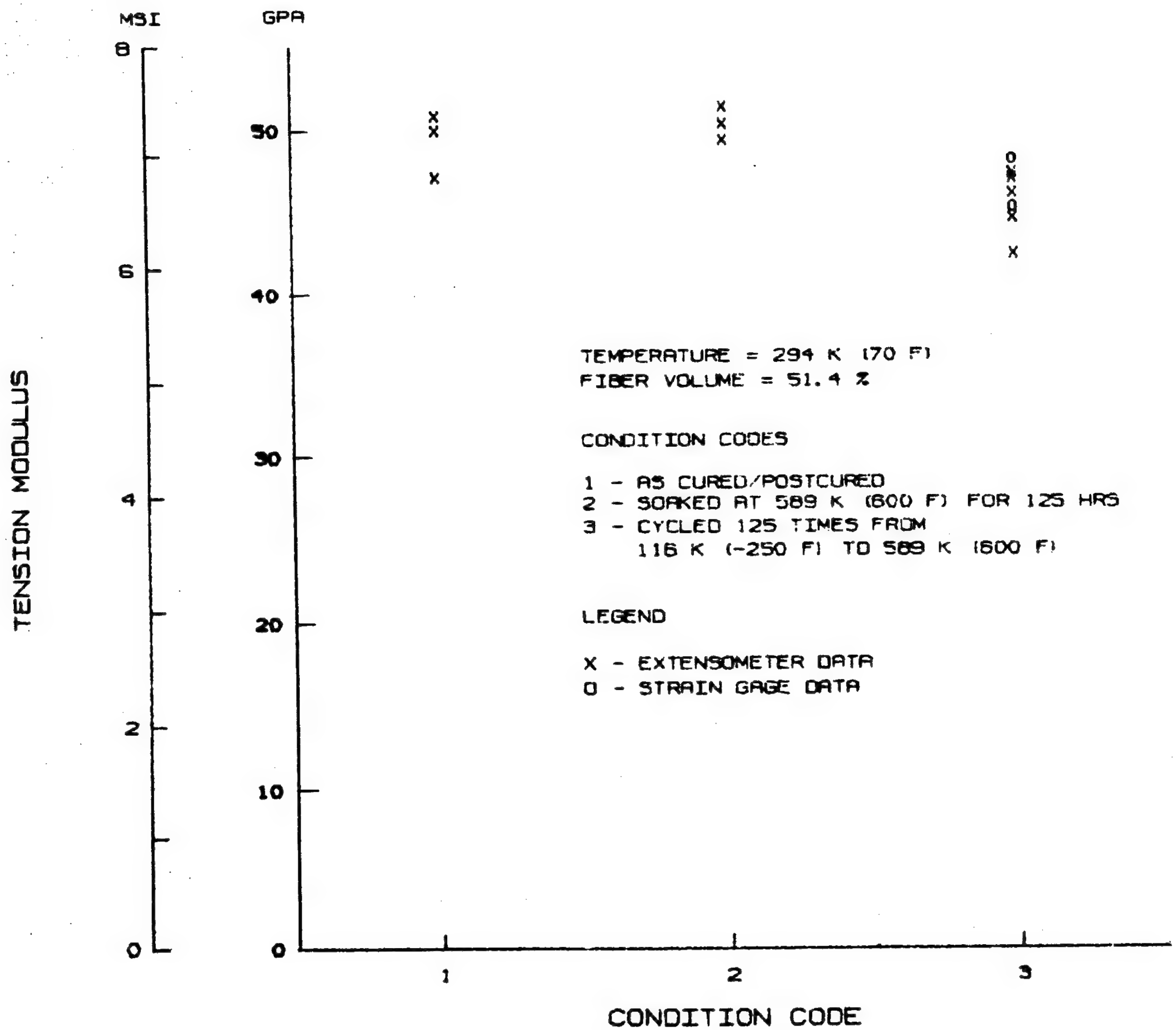


Figure 5.3-16: Celion 3000/PMR-15 Tension Tests $(0/\underline{+}45/90)_{4S}$ Layup 294K (70^{o}F) - Modulus

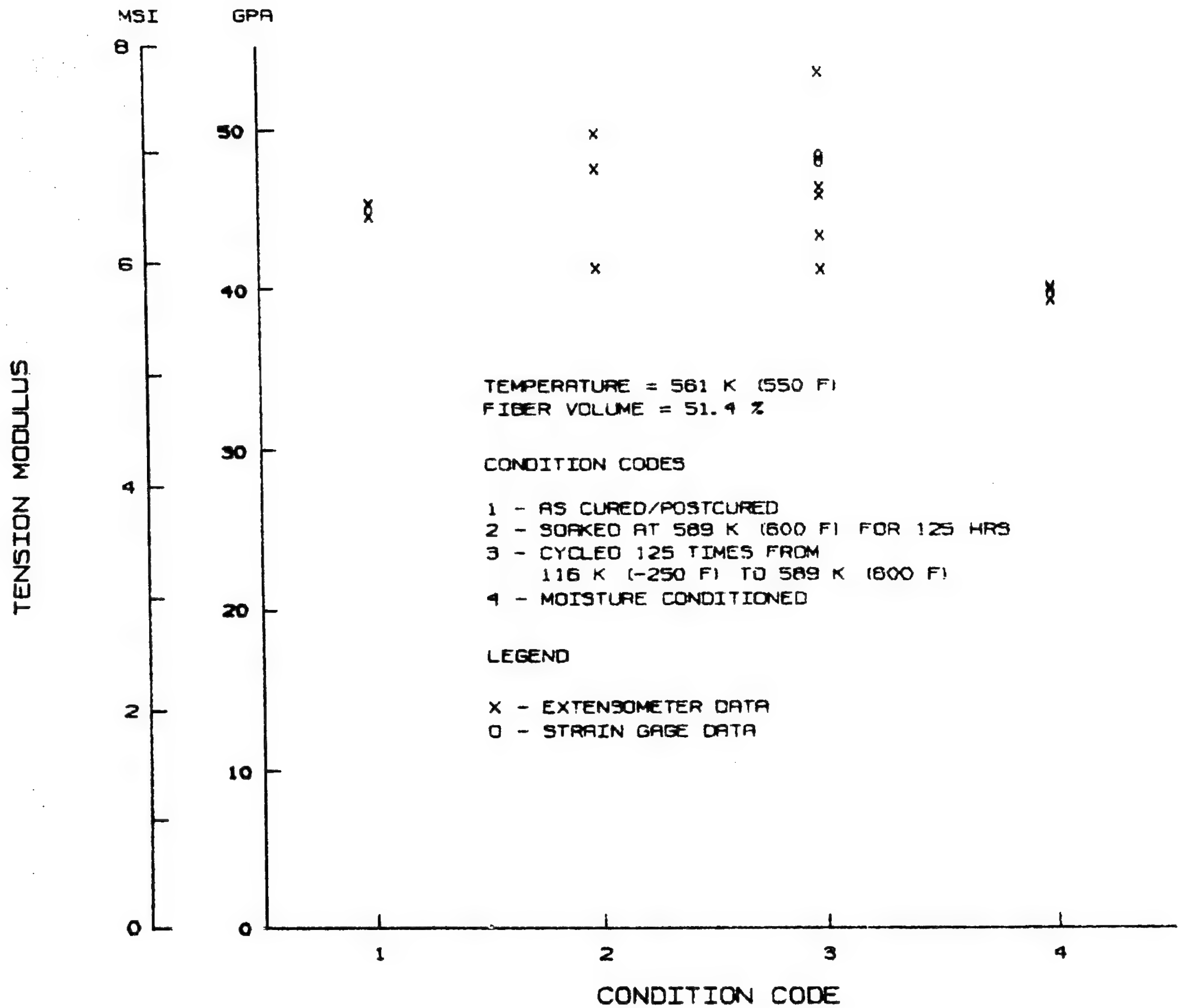


Figure 5.3-17: Celion 3000/PMR-15 Tension Tests $(0/\underline{+}45/90)_{4S}$ Layup 561K (550^{O}F) - Modulus

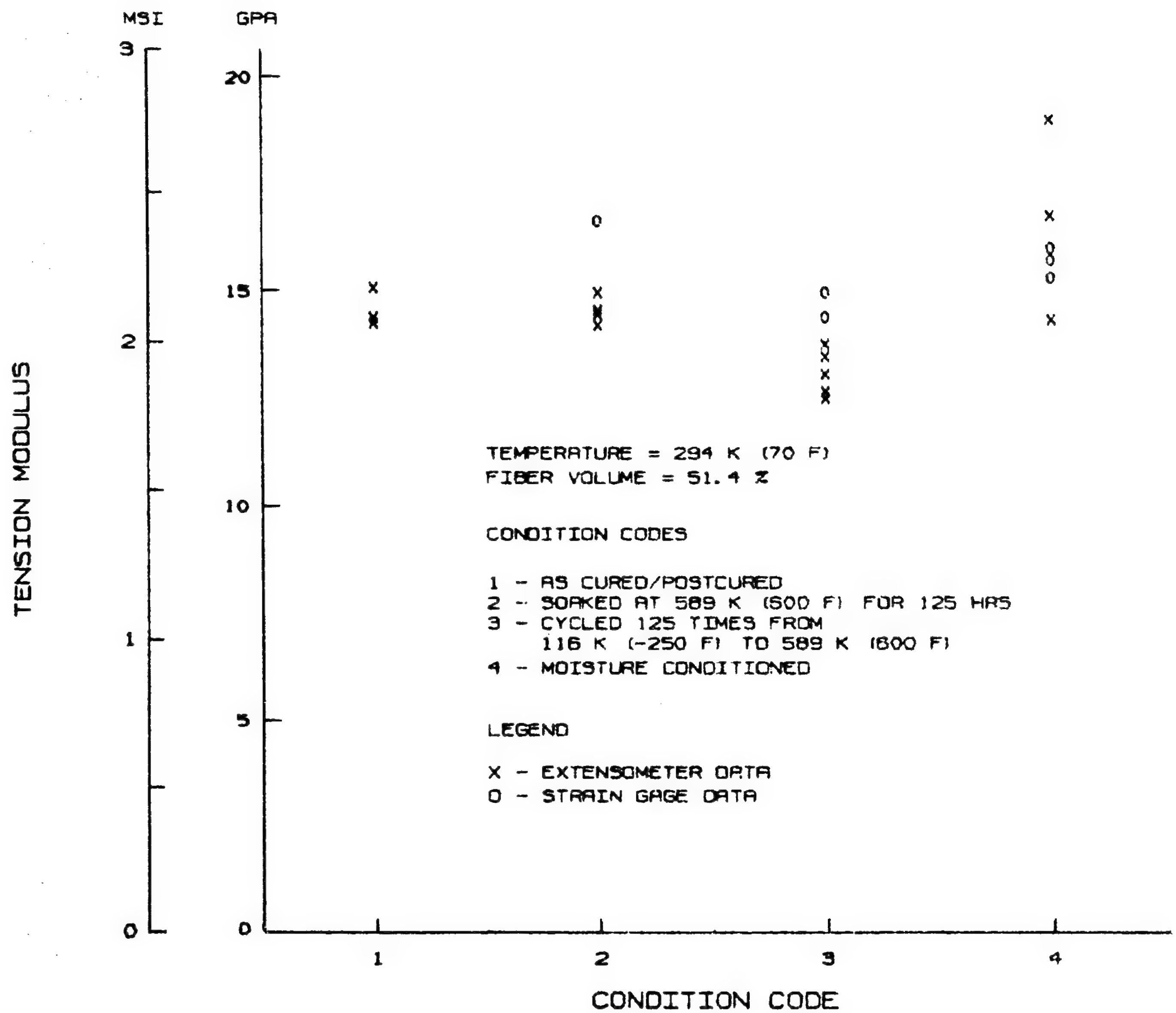


Figure 5.3-18: Celion 3000/PMR-15 Tension Tests $(\pm 45)_{8S}$ Layup 294K (70^{o}F) - Modulus

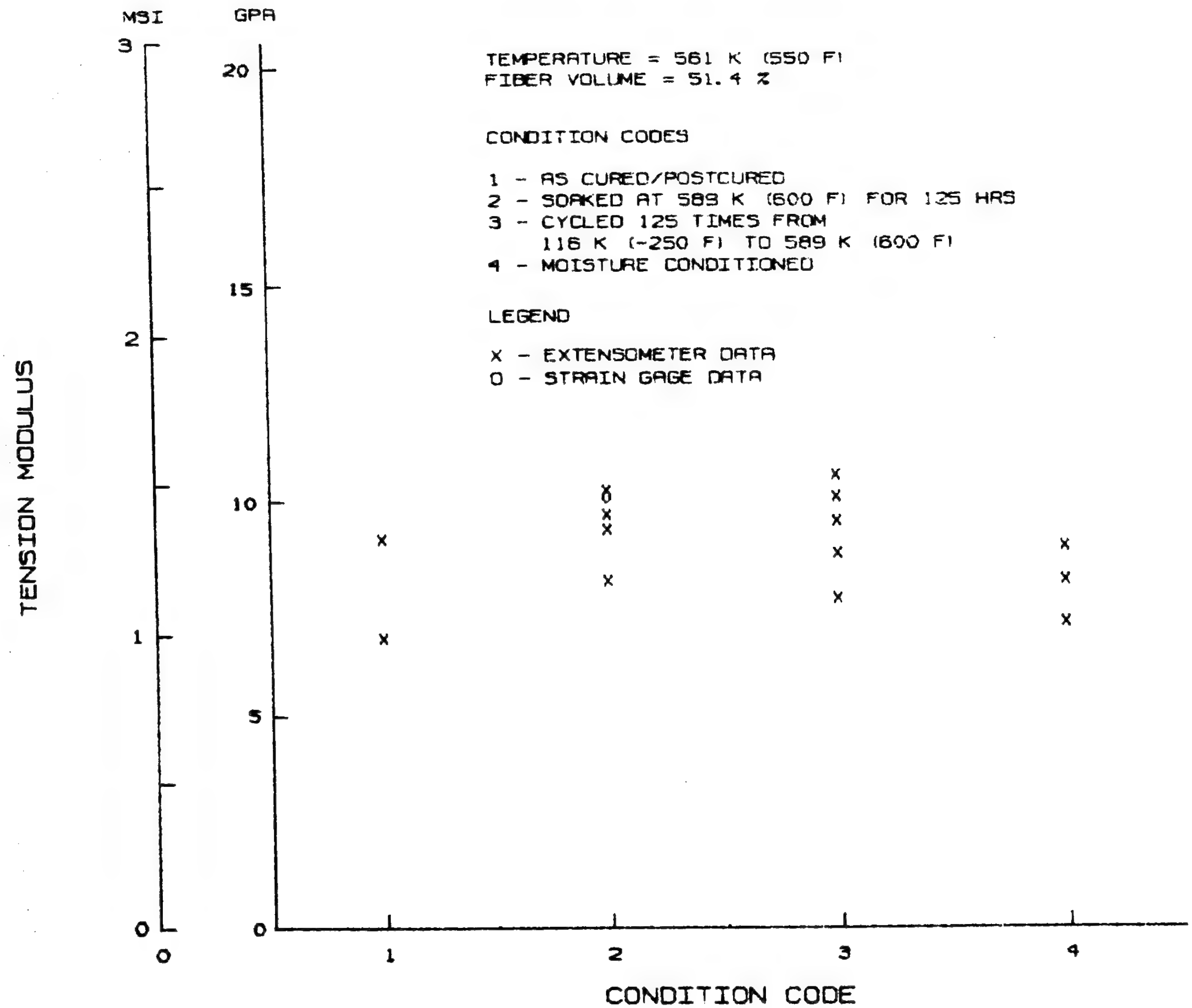


Figure 5.3-19: Celion 3000/PMR-15 Tension Tests $(\underline{+}45)_{8S}$ Layup 561K (550^{O}F) - Modulus

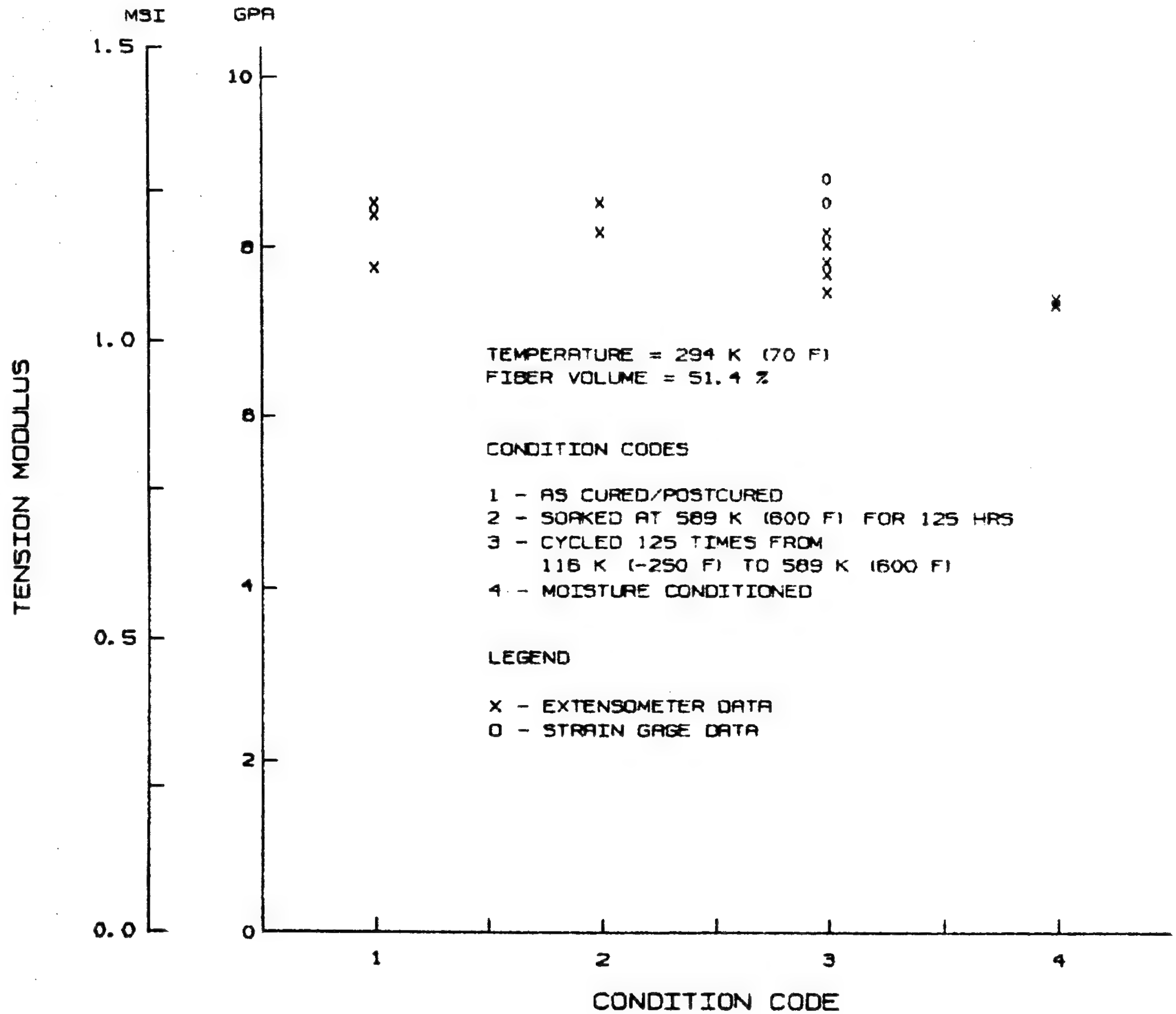


Figure 5.3-20: Celion 3000/PMR-15 Tension Tests $(90)_{30}$ Layup 294K (70^{o}F) - Modulus

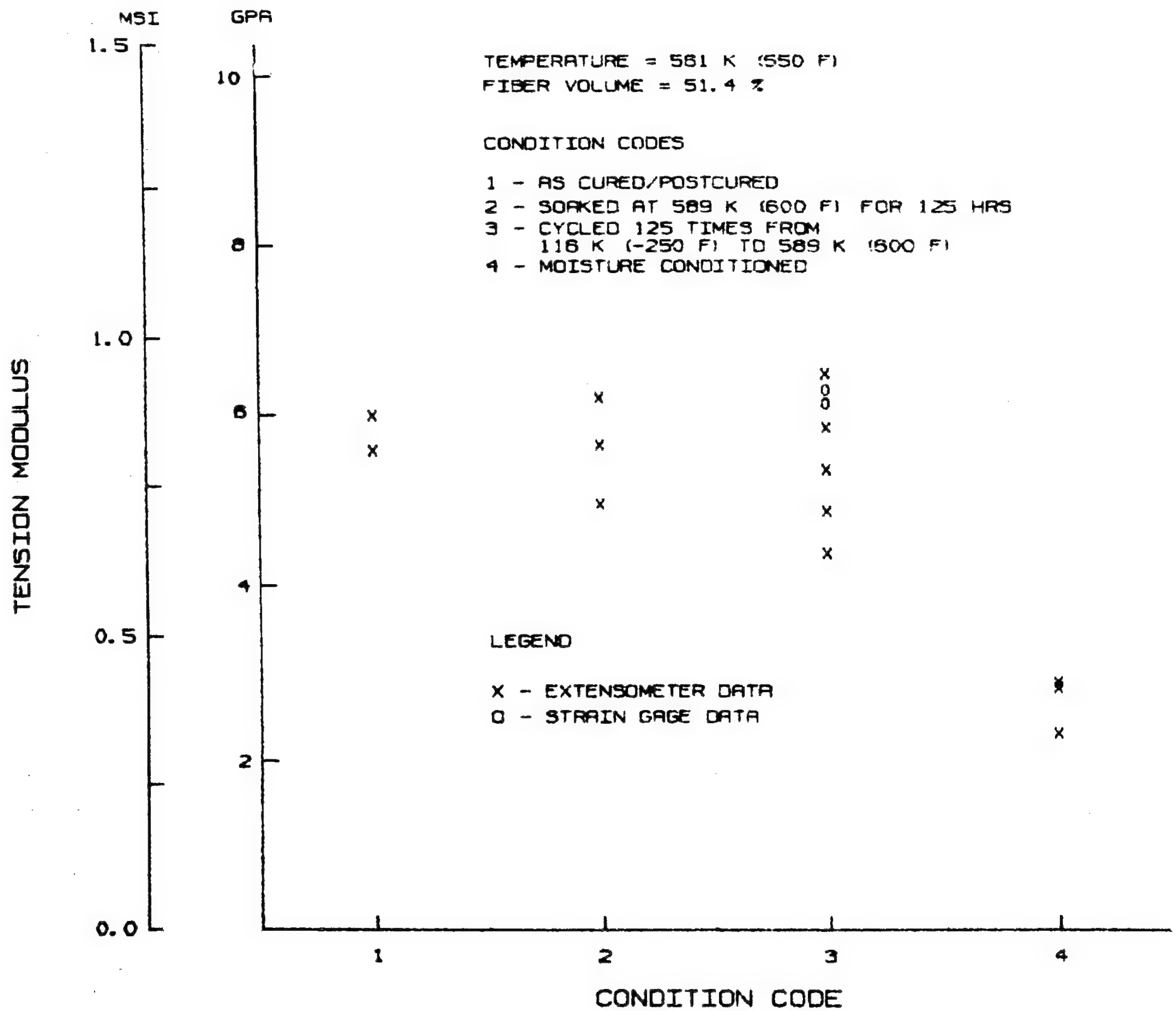


Figure 5.3-21: Celion 3000/PMR-15 Tension Tests $(90)_{30}$ Layup 561K (550^{0}F) - Modulus

5.4 Compression Tests

This section presents test procedures and test results for the compression tests of $(90/\pm45/0)_{4S}$ coupon specimens and $(0/\pm45/90)_S$ sandwich beam specimens.

5.4.1 Test Procedures

End loaded coupon compression tests (test 4 of Matrix 1) were conducted in accordance with ASTM D 695. Room temperature tests were conducted using the test fixture shown in Figure 5.4-1. It was subsequently discovered that this fixture could not be used for the elevated temperature tests. Elevated temperature tests were therefore conducted using the test fixture shown in Figure 5.4-2. The fixtures are similar, except for specimen size, and provide lateral support to prevent premature buckling. To provide a comparison between the two fixtures some room temperature tests were also run using the elevated temperature fixture. After conditioning, specimens were installed in the appropriate compression fixture. Extensometer clips were attached to the specimen using a 25.4mm (1.00 in.) gage length. A typical test setup is shown in Figures 5.4-3. No strain gages were used because of fixture space restrictions. Load was applied at a strain rate of 8.3×10^{-5} m/msec (.005 in/in-min).

Sandwich beam compression tests (test 5 of Matrix 1) were conducted in accordance with ASTM C393. A schematic of the test set-up is shown in Figure 5.4-4. Note that the test laminate was Celion 6000/PMR-15 instead of Celion 3000/PMR-15. After conditioning, the specimen was installed in the 4 point load fixture. Where applicable, strain gages were connected to an x-y plotter. Load was applied at a cross head speed of 2.1×10^{-5} m/sec (0.05 in/min).

5.4.2 Test Results

Test results are summarized in Tables 5.4-1 through 5.4-2. Typical failed specimens are shown in Figure 5.4-5 through 5.4-7.

Test results are plotted as functions of temperature and conditioning in Figures 5.4-8 through 5.4-13. The Celion 3000/PMR-15 shows a drop in strength at elevated temperature but no significant change in modulus. Conditioning did not affect the material performance. The Celion 6000/PMR-15 also showed a slight drop in strength at elevated temperature with no change in modulus.

Room temperature end loaded coupon tests were run using the two different test fixtures to enable a comparison of test results: Cured/Post Cured specimens differed by 11.8% while thermally cycled specimens differed by 5.5%. These differences are considered reasonable because of the small number of specimens.

A comparison between the coupon tests and the sandwich beam tests has also been made. Average compression failures stresses for the coupon specimens were 512 MPa (74.2 Ksi) and 413 MPa (59.9 Ksi) at room temperature and 561K (550^0F) respectively which are higher than the sandwich beam test results which were 452 MPa (65.6 Ksi) and 393 MPa (57.0 Ksi) respectively. Average compression moduli for the coupon tests were 38.7 GPa (5.62×10^6 psi) and 41.5 GPa (6.02×10^6 psi) at room temperature and 561K (550^0F) respectively which are lower than the sandwich beam test results which were 61.9 GPa (8.98×10^6 psi) and 59.9 GPa (8.68×10^6 psi) respectively. The compression moduli for the sandwich beam specimens are based on strain gages bonded to the outer or 0^0 ply. These differences in failure stress and moduli can be partially attributed to differences in material and layup. The coupon specimens had 90^0 plies on the outside which would provide buckling support to the primary load carrying 0^0 plies. This could result in a higher failure stress than when the 0^0 plies are on the outside as in the sandwich beam specimens. Examination of the sandwich beam specimens indicates a combined peel and buckling failure. Differences in moduli are attributed to differences in extensometer versus strain gage data.

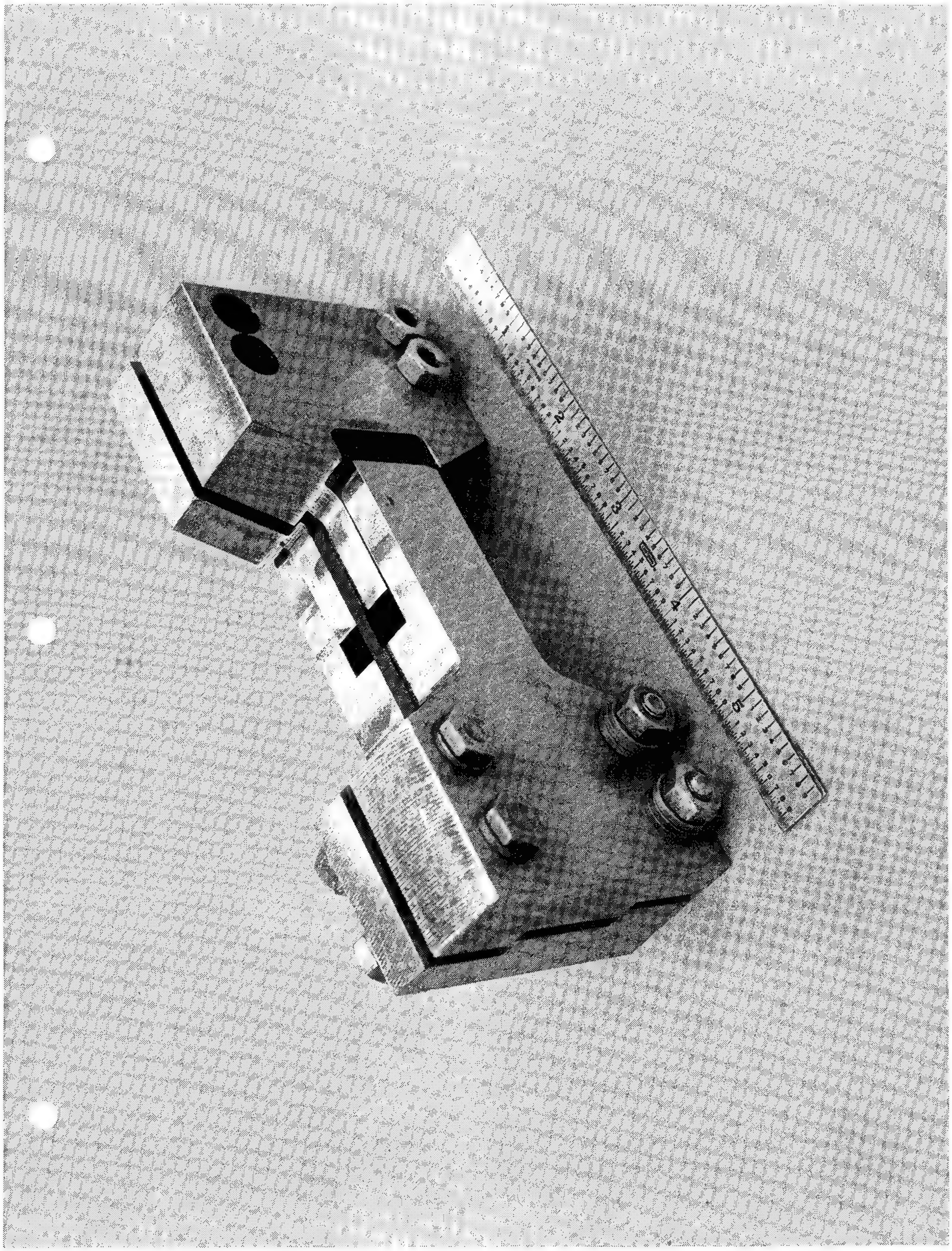


Figure 5.4-1: Compression Fixture 294K (70°F)

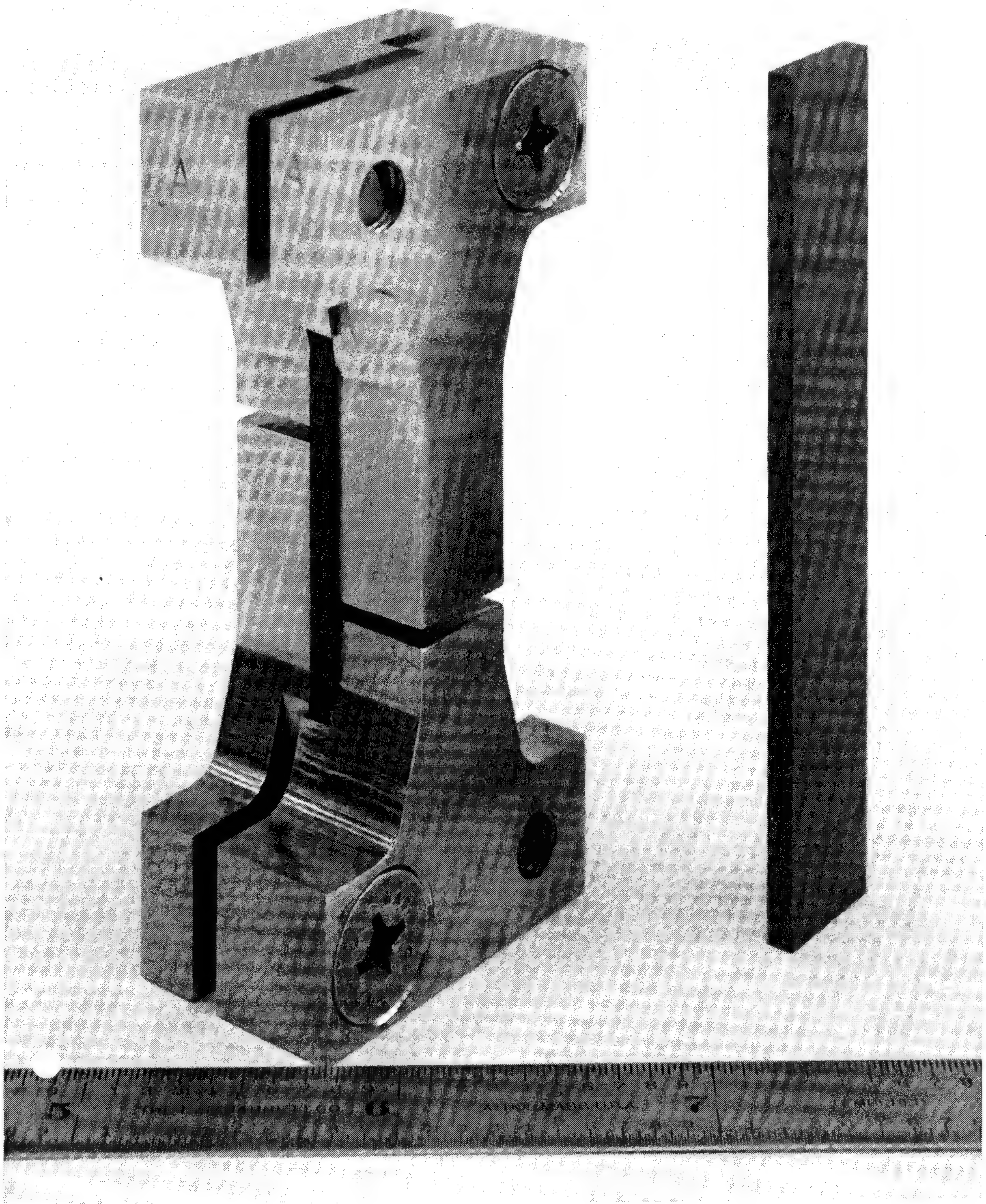


Figure 5.4-2: Compression Fixture 561K (550°F)

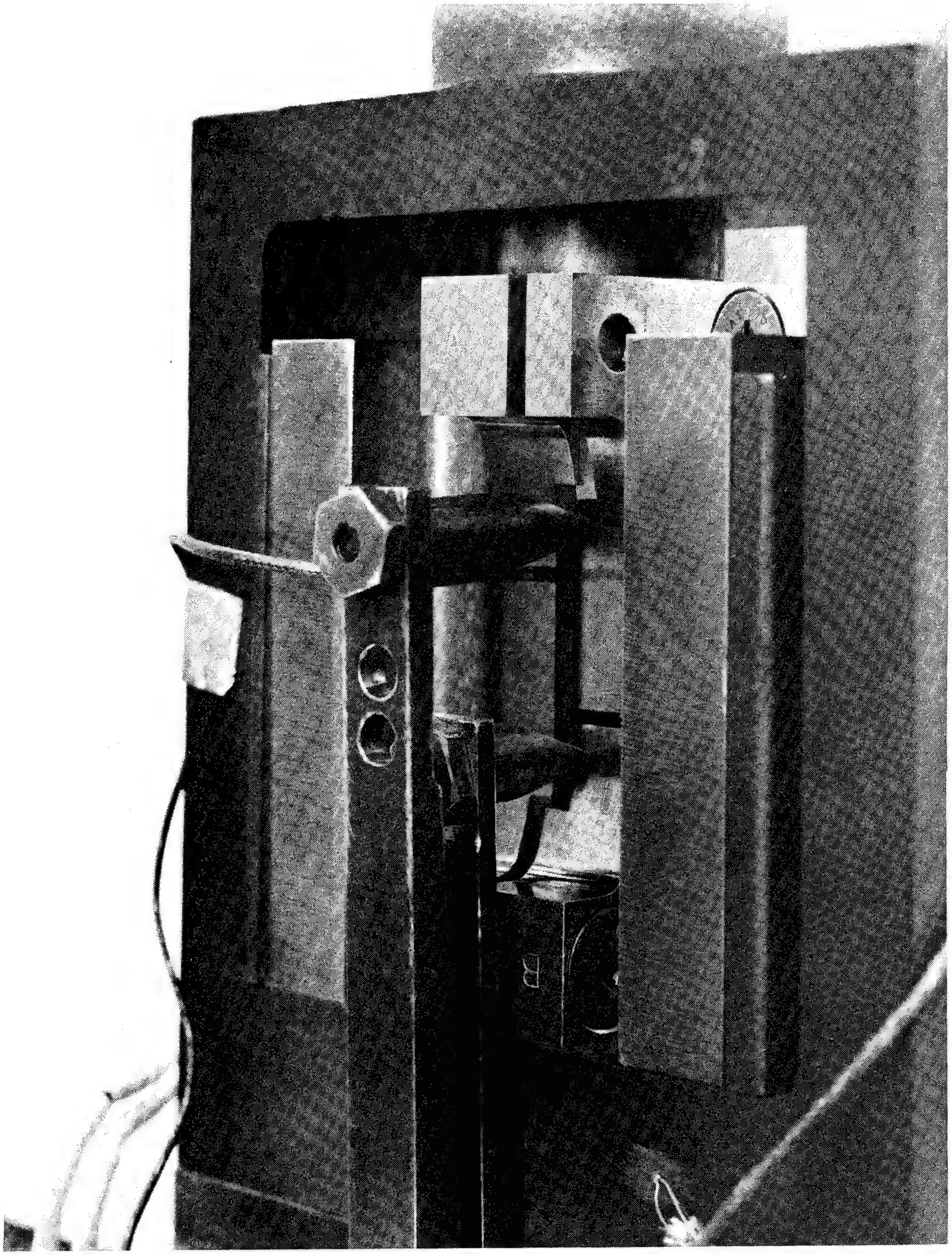


Figure 5.4-3: Typical Compression Test Setup

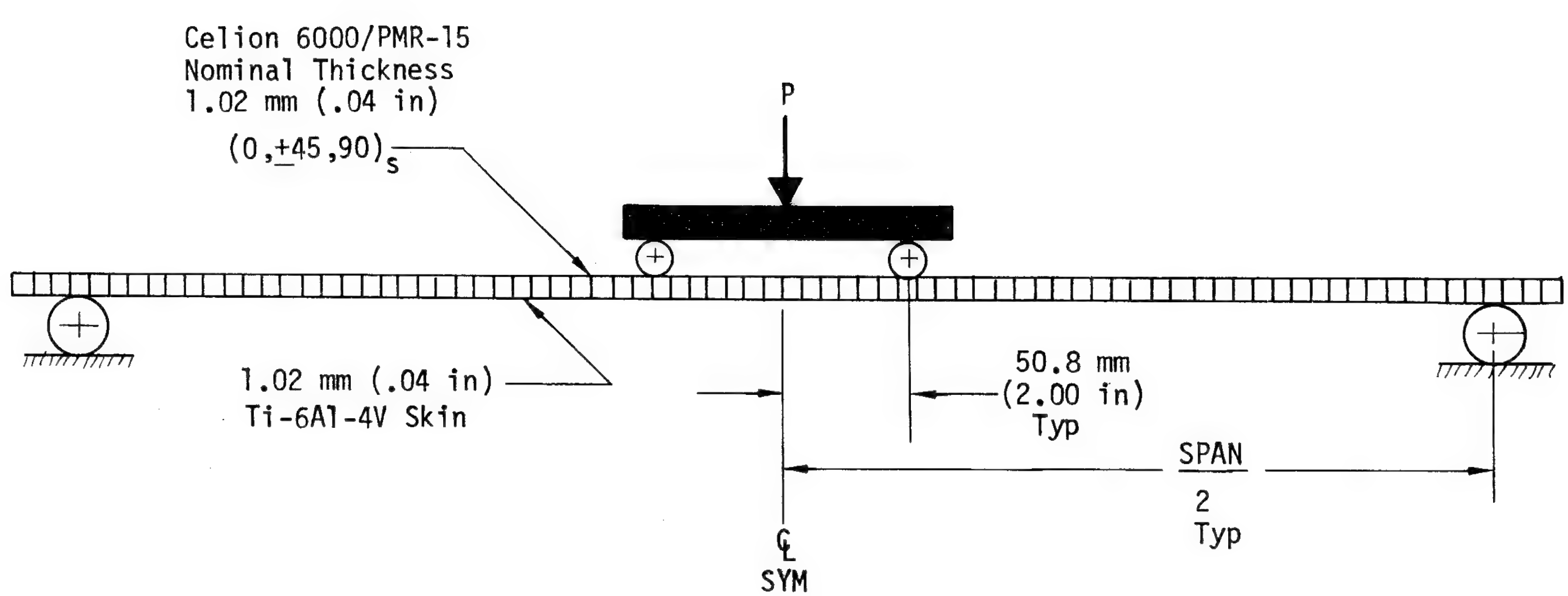


Figure 5.4-4: Celion 6000/PMR-15* Design Allowables Sandwich Beam Compression Test Setup (Schematic)

* Celion 6000/PMR-15 Was Substituted for Celion 3000/PMR-15

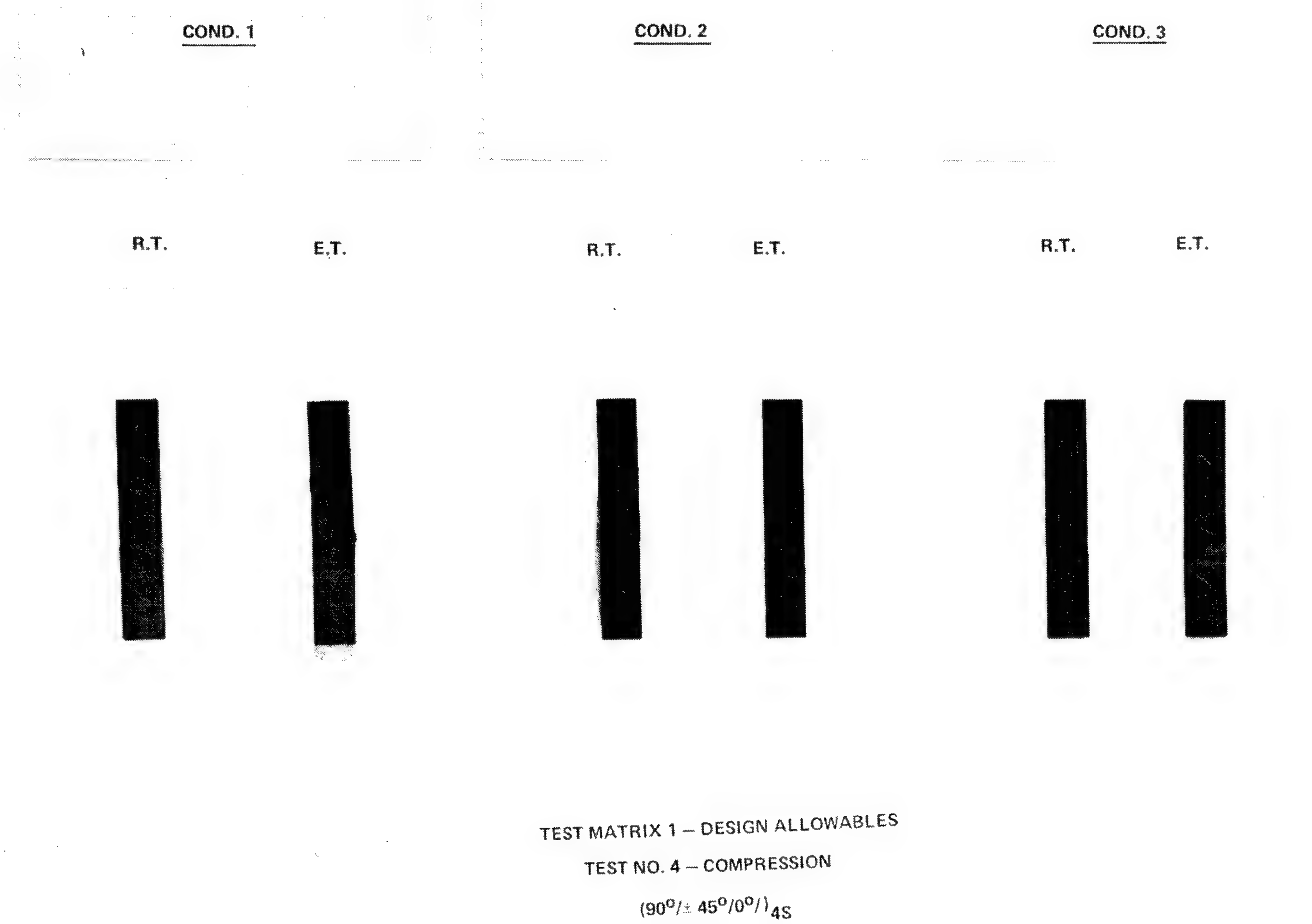


Figure 5.4-5: Celion 3000/PMR-15 Compression Tests $[90/\pm45/0]_{4S}$ Layup - Failed Specimens

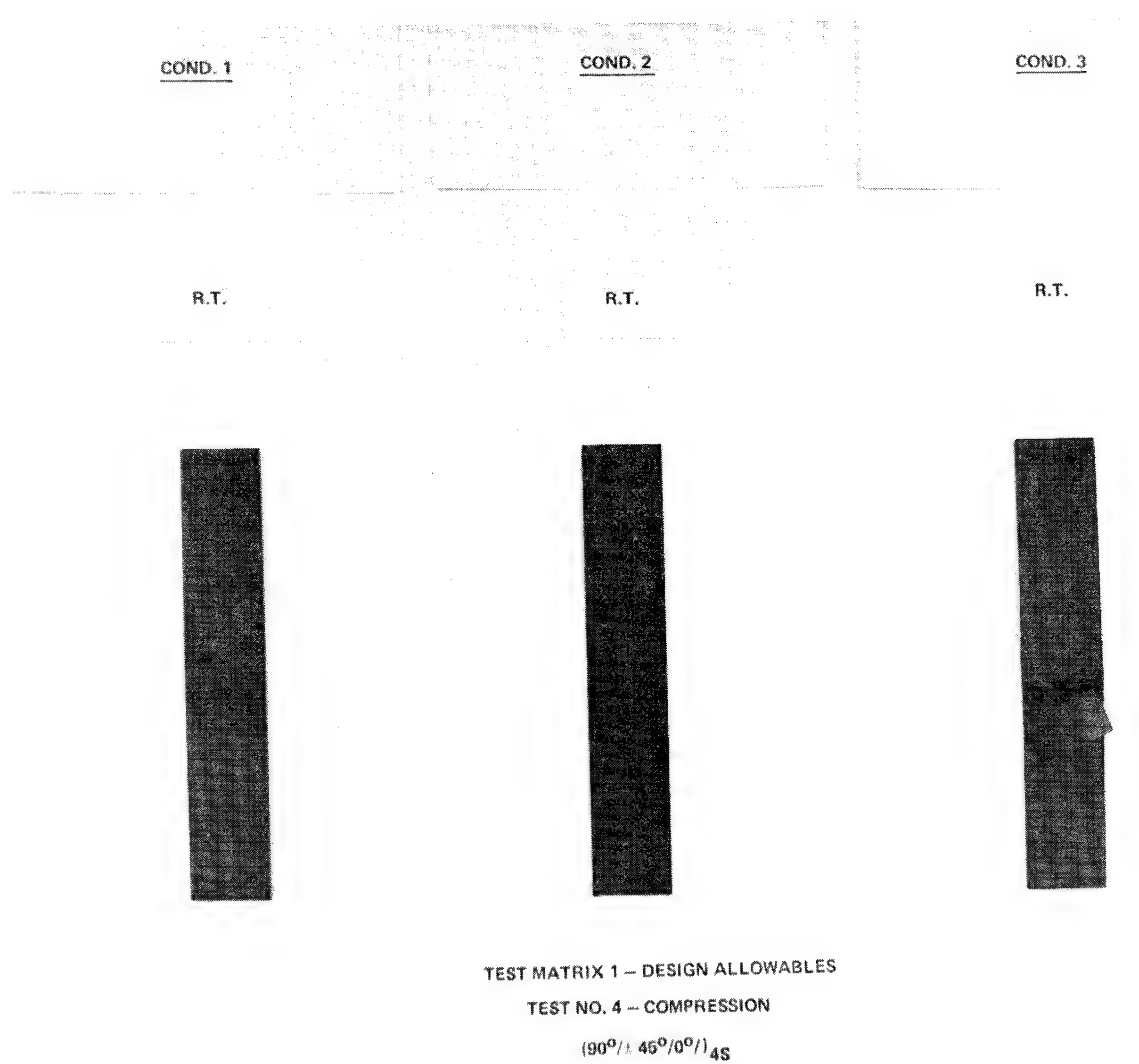
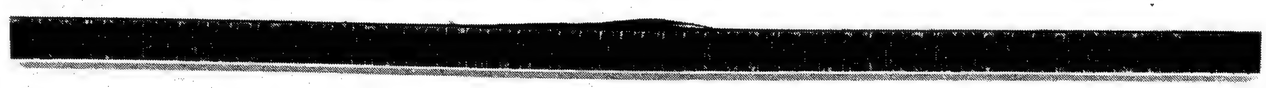


Figure 5.4-6: Celion 3000/PMR-15 Compression Tests $[90/\underline{+}45/0]_{4S}$ Layup - Failed Specimens



TEST TEMPERATURE = 294K (70°F)
CONDITIONING – AGED 125 HRS @ 589K (600°F)

TEST TEMPERATURE 561K (550°F)
CONDITIONING – AGED 125 HRS @ 589K (600°F)

Figure 5.4-7: Celion 6000/PMR-15 Sandwich Beam Compression Tests $[0/\pm45/90]_S$ Layup - Failed Specimens

TABLE 5.4-1. CELION 3000/PMR-15 DESIGN ALLOWABLES COMPRESSION TESTS [90/+-45/0]4S LAYUP

(a) SI UNITS

COND. CODE	SPECIMEN	FIXTURE USED	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA COMPRESSION MODULUS GPA
1	12A-1	FIG. 5.4-1	2.45	25.489	294.	33184.	532.	NO DATA	41.4
1	12A-2	FIG. 5.4-1	2.47	25.608	294.	33095.	523.	.0134	41.2
1	12A-3	FIG. 5.4-1	2.45	25.662	294.	31138.	496.	.0132	41.3
1	12A-4	FIG. 5.4-2	2.46	12.764	294.	18193.	578.	.0156	43.3
1	12A-5	FIG. 5.4-2	2.43	12.743	561.	18193.	589.	.0127	45.9
1	12A-6	FIG. 5.4-2	2.47	12.746	561.	15969.	506.	.0133	44.7
1	12A-7	FIG. 5.4-2	2.48	12.764	561.	12766.	403.	.0106	41.2
1	12A-8	FIG. 5.4-2	2.48	12.756	561.	12055.	381.	.0098	44.9
2	12B-1	FIG. 5.4-1	2.45	25.519	294.	29358.	470.	.0140	35.8
2	12B-2	FIG. 5.4-1	2.43	25.514	294.	30070.	485.	.0136	39.2
2	12B-3	FIG. 5.4-1	2.43	25.502	294.	34518.	558.	.0152	39.2
2	12B-5	FIG. 5.4-1	2.43	25.575	294.	33273.	534.	.0157	40.7
2	12B-4	FIG. 5.4-2	2.47	12.756	561.	12989.	412.	NO DATA	40.3
2	12B-7	FIG. 5.4-2	2.44	12.736	561.	12500.	403.	NO DATA	42.1
2	12B-8	FIG. 5.4-2	2.44	12.700	561.	13167.	425.	.0110	42.2
3	13B-1	FIG. 5.4-1	2.43	25.522	294.	30248.	487.	.0114	47.2
3	13B-2	FIG. 5.4-1	2.38	25.461	294.	31315.	518.	.0144	38.3
3	13B-3	FIG. 5.4-1	2.46	25.547	294.	36120.	576.	.0176	38.4
3	13B-4	FIG. 5.4-2	2.43	12.720	294.	17215.	556.	.0153	47.0
3	13B-5	FIG. 5.4-2	2.42	12.758	561.	12322.	399.	.0105	39.3
3	13B-6	FIG. 5.4-2	2.43	12.675	561.	12144.	394.	.0113	44.7
3	13B-7	FIG. 5.4-2	2.44	12.639	561.	13300.	430.	.0115	41.1
3	13B-8	FIG. 5.4-2	2.41	12.720	561.	14590.	477.	NO DATA	45.2
3	13B-9	FIG. 5.4-2	2.41	12.715	561.	12322.	402.	.0104	40.4
3	13B-10	FIG. 5.4-2	2.47	12.723	561.	14501.	461.	.0116	49.2
3	13B-11	FIG. 5.4-2	2.42	12.736	561.	14368.	467.	.0117	41.7
3	13B-12	FIG. 5.4-2	2.43	12.713	561.	17126.	554.	.0146	46.3

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.4-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	FIXTURE USED	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA COMPRESSION MODULUS MSI
1	12A-1	FIG. 5.4-1	.0964	1.0035	70.	7460.	77.1	NO DATA	6.01
1	12A-2	FIG. 5.4-1	.0972	1.0082	70.	7440.	75.9	.0134	5.97
1	12A-3	FIG. 5.4-1	.0964	1.0103	70.	7000.	71.9	.0132	5.99
1	12A-4	FIG. 5.4-2	.0970	0.5025	70.	4090.	83.9	.0156	6.28
1	12A-5	FIG. 5.4-2	.0955	0.5017	550.	4090.	85.4	.0127	6.65
1	12A-6	FIG. 5.4-2	.0974	0.5018	550.	3590.	73.4	.0133	6.48
1	12A-7	FIG. 5.4-2	.0978	0.5025	550.	2870.	58.4	.0106	5.98
1	12A-8	FIG. 5.4-2	.0976	0.5022	550.	2710.	55.3	.0098	6.51
2	12B-1	FIG. 5.4-1	.0963	1.0047	70.	6600.	68.2	.0140	5.19
2	12B-2	FIG. 5.4-1	.0956	1.0045	70.	6760.	70.4	.0136	5.68
2	12B-3	FIG. 5.4-1	.0955	1.0040	70.	7760.	80.9	.0152	5.69
2	12B-5	FIG. 5.4-1	.0958	1.0069	70.	7480.	77.5	.0157	5.90
2	12B-4	FIG. 5.4-2	.0973	0.5022	550.	2920.	59.7	NO DATA	5.84
2	12B-7	FIG. 5.4-2	.0960	0.5014	550.	2810.	58.4	NO DATA	6.10
2	12B-8	FIG. 5.4-2	.0961	0.5000	550.	2960.	61.6	.0110	6.12
3	13B-1	FIG. 5.4-1	.0958	1.0048	70.	6800.	70.6	.0114	6.84
3	13B-2	FIG. 5.4-1	.0936	1.0024	70.	7040.	75.1	.0144	5.56
3	13B-3	FIG. 5.4-1	.0967	1.0058	70.	8120.	83.5	.0176	5.57
3	13B-4	FIG. 5.4-2	.0958	0.5008	70.	3870.	80.6	.0153	6.82
3	13B-5	FIG. 5.4-2	.0954	0.5023	550.	2770.	57.8	.0105	5.70
3	13B-6	FIG. 5.4-2	.0956	0.4990	550.	2730.	57.2	.0113	6.48
3	13B-7	FIG. 5.4-2	.0962	0.4976	550.	2990.	62.4	.0115	5.96
3	13B-8	FIG. 5.4-2	.0947	0.5008	550.	3280.	69.2	NO DATA	6.55
3	13B-9	FIG. 5.4-2	.0950	0.5006	550.	2770.	58.3	.0104	5.86
3	13B-10	FIG. 5.4-2	.0973	0.5009	550.	3260.	66.9	.0116	7.13
3	13B-11	FIG. 5.4-2	.0952	0.5014	550.	3230.	67.7	.0117	6.05
3	13B-12	FIG. 5.4-2	.0958	0.5005	550.	3850.	80.4	.0146	6.71

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.4-2. CELION 6000/PMR-15 DESIGN ALLOWABLES SANDWICH BEAM COMPRESSION TESTS [0/+-45/90]S LAYUP

(a) SI UNITS

COND. CODE	SPECIMEN	WIDTH MM	THICKNESS MM	SPAN MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	COMPRESSION MODULUS GPA
2	1-5-2-1	23.8	1.	559.	294.	1524.	464.	63.1
2	1-5-2-3	23.8	1.	559.	294.	2217.	523.	NO DATA
2	1-5-2-4	23.8	1.	559.	294.	1933.	455.	NO DATA
2	1-12-2-1	23.8	1.	559.	294.	1773.	416.	60.7
2	1-12-2-3	23.7	1.	559.	294.	1710.	404.	NO DATA
2	1-12-2-4	23.6	1.	559.	294.	1897.	450.	NO DATA
2	1-5-2-2	23.7	1.	584.	561.	1848.	461.	59.8
2	1-5-2-5	23.9	1.	584.	561.	1555.	385.	NO DATA
2	1-5-2-6	23.0	1.	584.	561.	1786.	459.	NO DATA
2	1-12-2-2	23.7	1.	584.	561.	1555.	387.	60.0
2	1-12-2-5	23.7	1.	559.	561.	1461.	346.	NO DATA
2	1-12-2-6*	23.8	1.	559.	561.	1759.	318.	NO DATA

* FAILED OUTSIDE OF TEST SECTION

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	WIDTH IN	THICKNESS IN	SPAN IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	COMPRESSION MODULUS MSI
2	1-5-2-1	.936	.04	22.	70.	342.5	67.3	9.15
2	1-5-2-3	.936	.04	22.	70.	498.5	75.8	NO DATA
2	1-5-2-4	.937	.04	22.	70.	434.5	66.0	NO DATA
2	1-12-2-1	.936	.04	22.	70.	398.5	60.3	8.80
2	1-12-2-3	.935	.04	22.	70.	384.5	58.6	NO DATA
2	1-12-2-4	.930	.04	22.	70.	426.5	65.3	NO DATA
2	1-5-2-2	.935	.04	23.	550.	415.5	66.8	8.67
2	1-5-2-5	.942	.04	23.	550.	349.5	55.8	NO DATA
2	1-5-2-6	.906	.04	23.	550.	401.5	66.6	NO DATA
2	1-12-2-2	.934	.04	23.	550.	349.5	56.2	8.70
2	1-12-2-5	.932	.04	22.	550.	328.5	50.2	NO DATA
2	1-12-2-6*	.936	.04	22.	550.	395.5	46.1	NO DATA

* FAILED OUTSIDE OF TEST SECTION

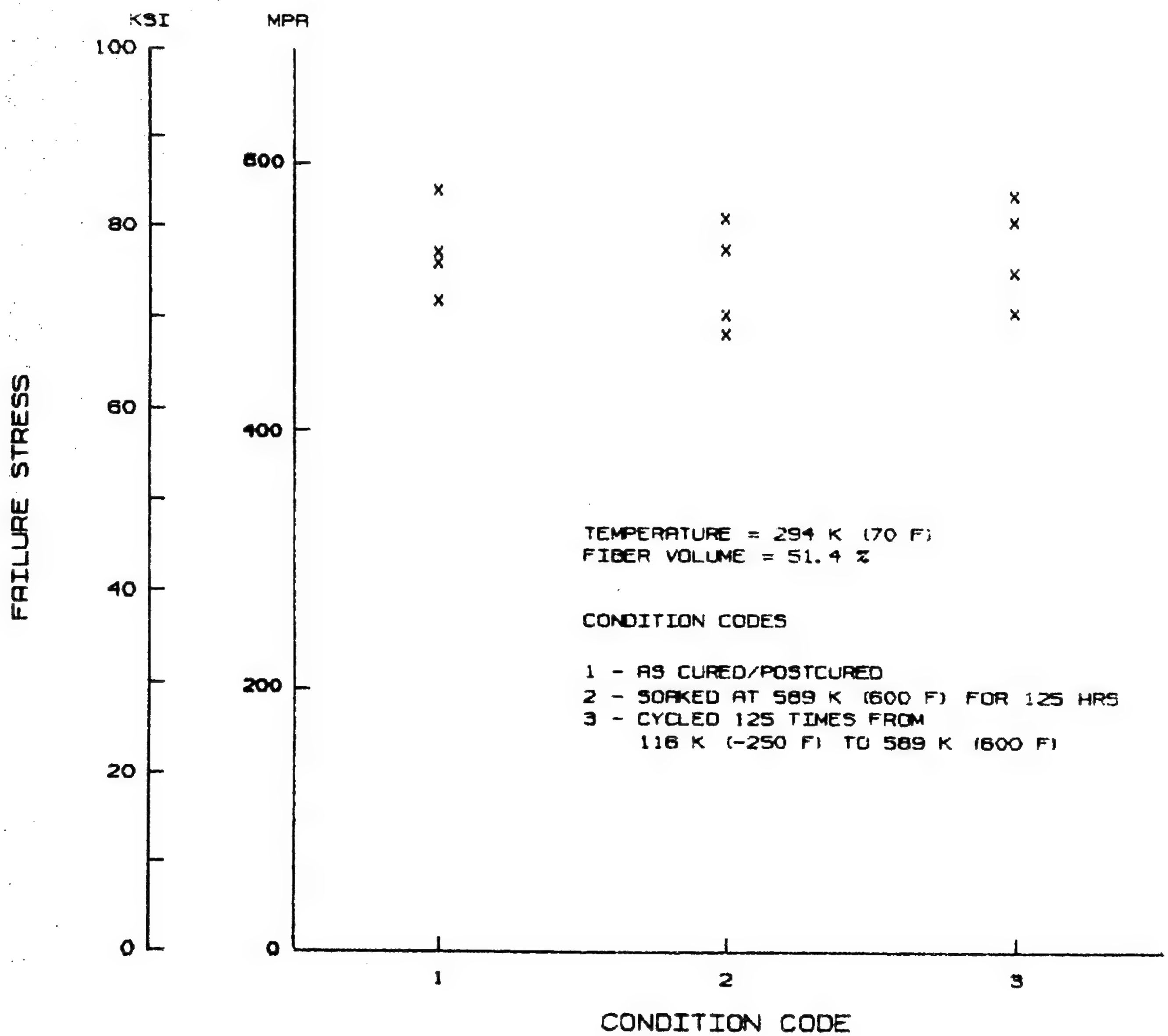


Figure 5.4-8: Celion 3000/PMR-15 Compression Tests $(90/\underline{+}45/0)_{4S}$ Layup 294K (70^{o}F) - Failure Stress

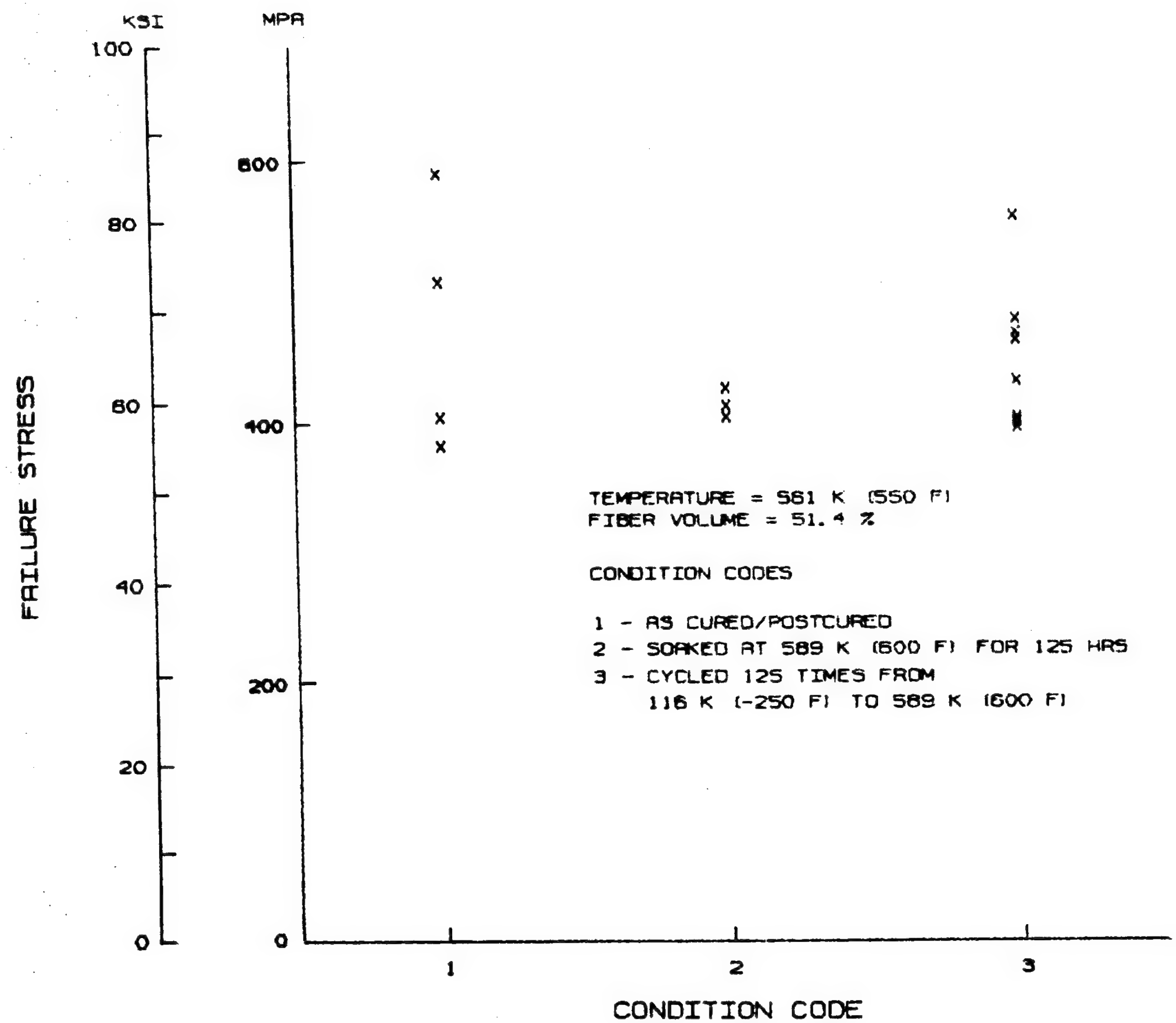


Figure 5.4-9: Celion 3000/PMR-15 Compression Tests $(90/\underline{+}45/0)_{4S}$ Layup 561K (550^{0}F) - Failure Stress

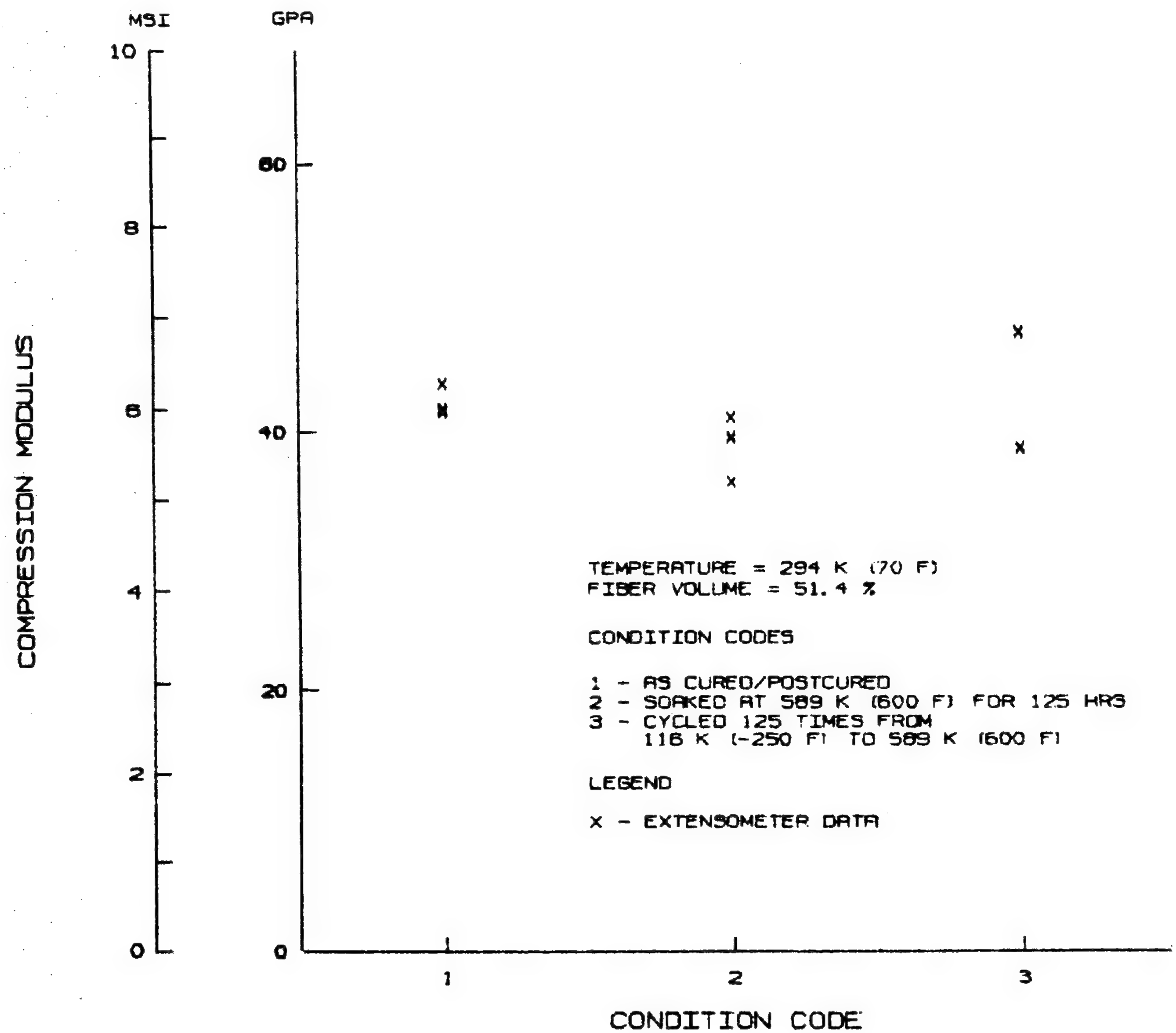


Figure 5.4-10: Celion 3000/PMR-15 Compression Tests $(90/\underline{+}45/0)_{4S}$ Layup 294K (70^{o}F) - Modulus

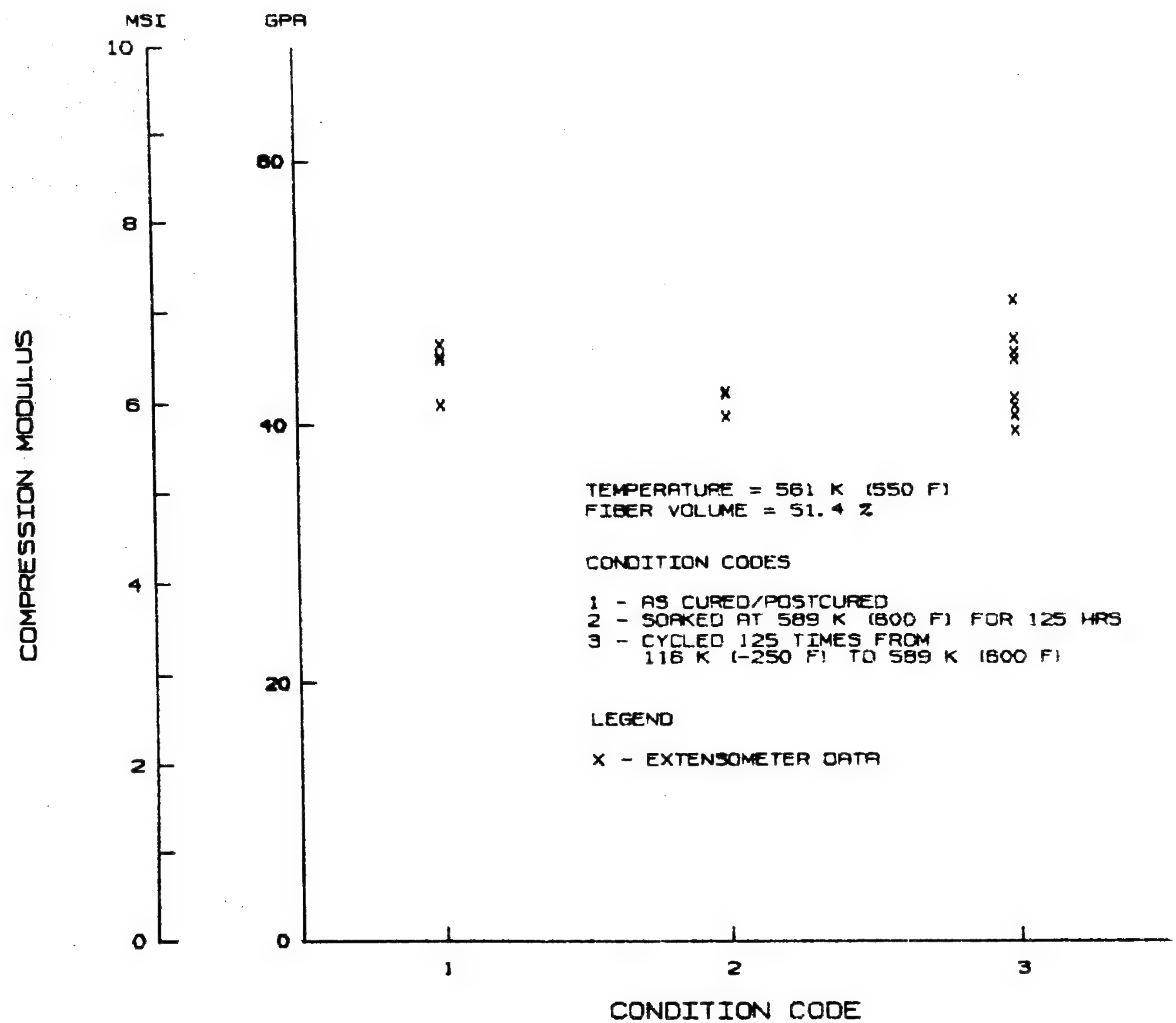


Figure 5.4-11: Celion 3000/PMR-15 Compression Tests $(90/\underline{+}45/0)_{4S}$ Layup 561K (550^{o}F) - Modulus

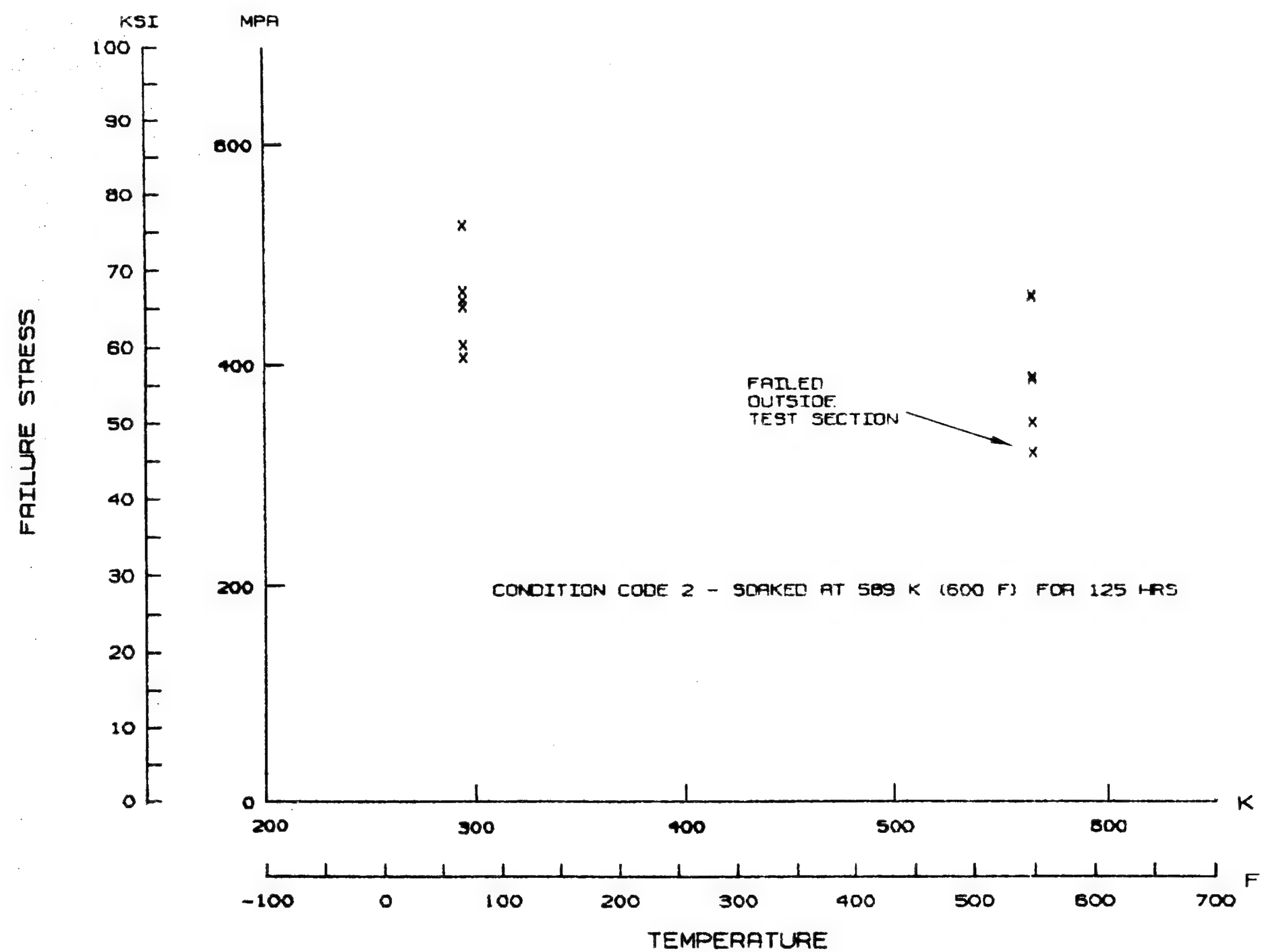


Figure 5.4-12: Celion 6000/PMR-15 Sandwich Beam Compression Tests $(0/\pm45/90)_S$ Layup - Failure Stress

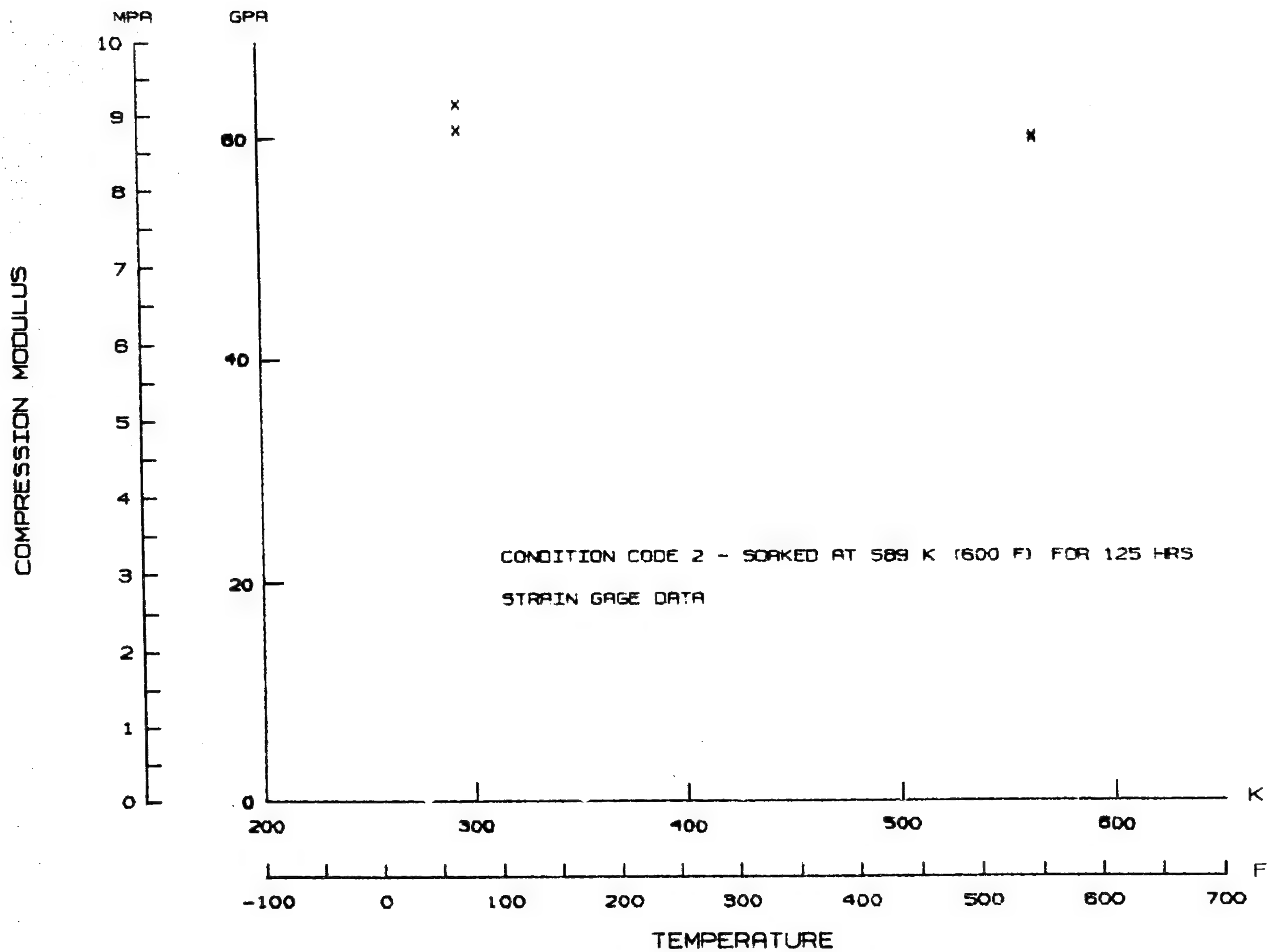


Figure 5.4-13: Celion 6000/PMR-15 Sandwich Beam Compression Tests $(0/\pm45/90)_S$ Layup - Modulus

5.5 Flatwise (Out-of-Plane Tension Tests)

This section presents test procedures and test results for flatwise (out-of-plane) tension tests of a $(0/\pm 45/90)_{2S}$ laminate and of a $(0/\pm 45/90)_{2S}$ laminate bonded to a honeycomb core.

5.5.1 Test Procedures

Flatwise tension tests of a laminate (test 7 of Matrix 1) were conducted in accordance with ASTM D2095. Flatwise tension tests of a laminate bonded to honeycomb core (test 8 of Matrix 1) were conducted in accordance with ASTM C297. Typical test set ups are shown in Figure 5.5-1 and 5.5.2 respectively. After conditioning, specimens were installed in a Baldwin Universal test machine. Load was applied at a cross head speed of 2.1×10^{-5} m/sec (.05 in/min) until failure.

5.5.2 Test Results

Test results are summarized in Tables 5.5-1 and 5.5-2. Typical failed specimens are shown in Figures 5.5-3 and 5.5-4.

Test results are plotted as a function of temperature and conditioning in Figures 5.5-5 through 5.5-10.

Data for laminate-to-laminate tests indicate a drop in strength at elevated temperature. This is as expected since transverse tension is controlled by the matrix strength. There also seems to be a reduction in strength due to aging except at elevated temperature where aged specimens are not significantly different than cured/post cured specimens (see Figure 5.5-7).

Test results for the laminate to core tests at 116K (-250^{0}F) are not conclusive because of premature failures. These failures were probably

caused by large thermal stresses due to the aluminum load blocks. The elevated temperature laminate-to-core tests had steel load blocks. Seven of the eight specimens at elevated temperatures had adhesive failures at the laminate to load block interface and are also not conclusive test results. Room temperature test results (Fig. 5.5-9) show a drop in strength due to aging.

A comparison of room temperature test results for the laminate only tests and the laminate-to-core tests is shown in Figure 5.5-11. As can be seen there is a large difference in failure stress although all specimens had the same failure mode. This is attributed to the difference in specimen geometry and points out the need for standardization of test procedures. In addition, application of test results to design practice must account for any differences in loading condition.

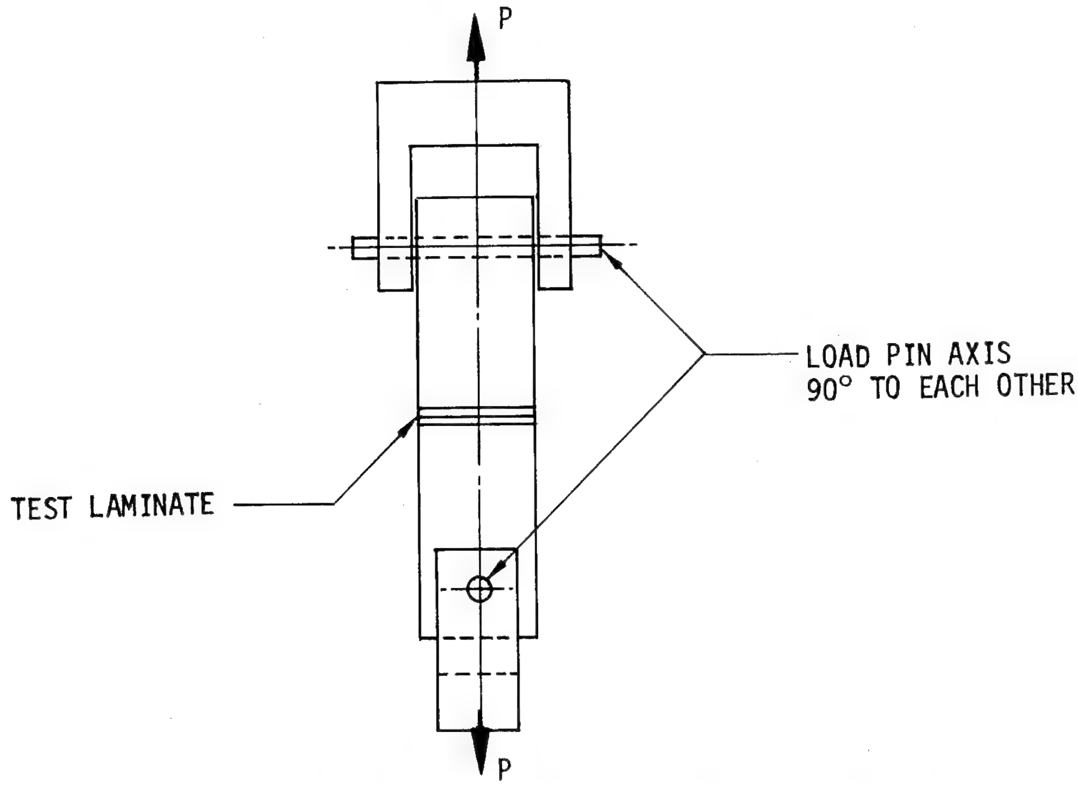


Figure 5.5-1: Celion 3000/PMR-15 Design Allowables Flatwise Laminate-to-Laminate Tension Test Setup

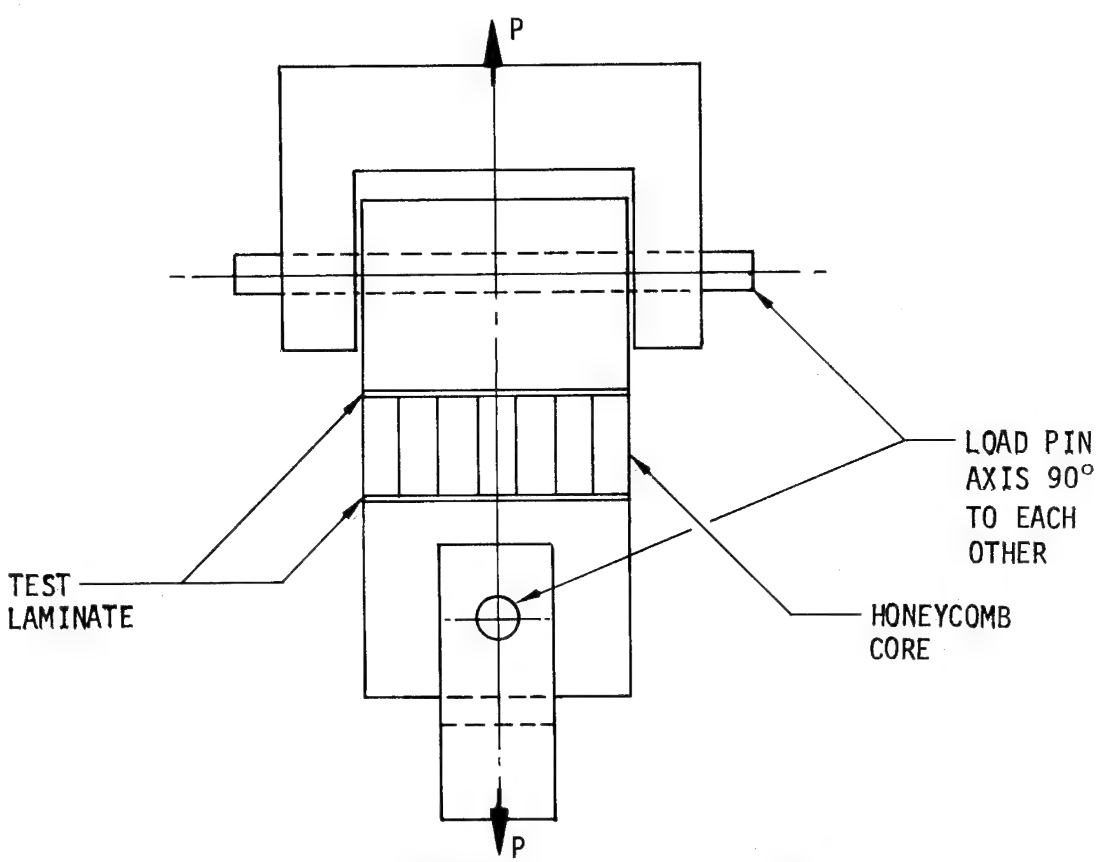


Figure 5.5-2: Celion 3000/PMR-15 Design Allowables Flatwise Laminate-to-Core Tension Test Setup

TABLE 5.5-1. CELION 3000/PMR-15 DESIGN ALLOWABLES FLATWISE LAMINATE TO LAMINATE TENSION TESTS
[0/+-45/90]2S LAYUP

(a) SI UNITS

COND. CODE	SPECIMEN	AREA SQ MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	FAILURE MODE
1	1-7-1-17	788.4	116.	21885.	27.76	INTERLAMINAR
1	1-7-1-18	767.7	116.	10275.	13.38	ADHESIVE
1	1-7-1-19	786.5	116.	16636.	21.15	INTERLAMINAR
1	1-7-1-14	785.2	294.	20862.	26.57	INTERLAMINAR
1	1-7-1-15	787.1	294.	20996.	26.68	INTERLAMINAR
1	1-7-1-16	789.7	294.	20551.	26.02	INTERLAMINAR
1	1-7-1-11	788.4	561.	6966.	8.84	INTERLAMINAR
1	1-7-1-12	787.7	561.	8176.	10.35	INTERLAMINAR
1	1-7-1-13	787.7	561.	5783.	7.34	COHESIVE
2	1-7-2-7	787.7	116.	3212.	4.07	BAD BOND
2	1-7-2-8	785.2	116.	11743.	14.91	INTERLAMINAR
2	1-7-2-9	786.5	116.	11165.	14.17	INTERLAMINAR
2	1-7-2-1	785.2	294.	8674.	11.03	INTERLAMINAR
2	1-7-2-2	786.5	294.	12544.	15.95	INTERLAMINAR
2	1-7-2-3	785.2	294.	10209.	12.98	INTERLAMINAR
2	1-7-2-4	787.7	561.	8674.	11.01	70% INTERLAMINAR 30% COHESIVE
2	1-7-2-5	787.7	561.	10453.	13.27	INTERLAMINAR
2	1-7-2-6	786.5	561.	4448.	5.65	BAD BOND

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.5-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	AREA SQ IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	FAILURE MODE
1	1-7-1-17	1.222	-250.	4920.	4.026	INTERLAMINAR
1	1-7-1-18	1.190	-250.	2310.	1.941	ADHESIVE
1	1-7-1-19	1.219	-250.	3740.	3.067	INTERLAMINAR
1	1-7-1-14	1.217	70.	4690.	3.854	INTERLAMINAR
1	1-7-1-15	1.220	70.	4720.	3.869	INTERLAMINAR
1	1-7-1-16	1.224	70.	4620.	3.775	INTERLAMINAR
1	1-7-1-11	1.222	550.	1566.	1.282	INTERLAMINAR
1	1-7-1-12	1.221	550.	1838.	1.501	INTERLAMINAR
1	1-7-1-13	1.221	550.	1300.	1.064	COHESIVE
2	1-7-2-7	1.221	-250.	722.	0.591	BAD BOND
2	1-7-2-8	1.217	-250.	2640.	2.162	INTERLAMINAR
2	1-7-2-9	1.219	-250.	2510.	2.055	INTERLAMINAR
2	1-7-2-1	1.217	70.	1950.	1.600	INTERLAMINAR
2	1-7-2-2	1.219	70.	2820.	2.313	INTERLAMINAR
2	1-7-2-3	1.217	70.	2295.	1.882	INTERLAMINAR
2	1-7-2-4	1.221	550.	1950.	1.597	70% INTERLAMINAR 30% COHESIVE
2	1-7-2-5	1.221	550.	2350.	1.924	INTERLAMINAR
2	1-7-2-6	1.219	550.	1000.	0.819	BAD BOND

NOTE: FIBER VOLUME = 51.4 %

TABLE 5.5-2. CELION 3000/PMR-15 DESIGN ALLOWABLES FLATWISE LAMINATE TO CORE TENSION TESTS
[0/+-45/90]2S LAYUP WITH HONEYCOMB CORE

(a) SI UNITS

COND. CODE	SPECIMEN	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS KPA	FAILURE MODE
1	1-8-1-4	116.	*	*	INTERLAMINAR
1	1-8-1-5	116.	6405.	2482.	ADHESIVE
1	1-8-1-6	116.	2802.	1089.	ADHESIVE
1	1-8-1-1	294.	17014.	6591.	INTERLAMINAR
1	1-8-1-2	294.	17548.	6798.	INTERLAMINAR + 25% CORE
1	1-8-1-3	294.	13678.	5302.	INTERLAMINAR
1	1-8-1-7	561.	7896.	3137.	ADHESIVE
1	1-8-1-8	561.	6383.	2537.	ADHESIVE
1	1-8-1-9	561.	4470.	1731.	ADHESIVE
1	1-8-1-10	561.	6561.	2544.	ADHESIVE
2	1-8-2-4	116.	*	*	INTERLAMINAR
2	1-8-2-5	116.	*	*	INTERLAMINAR
2	1-8-2-6	116.	*	*	INTERLAMINAR
2	1-8-2-1	294.	13122.	5109.	INTERLAMINAR
2	1-8-2-2	294.	13233.	5130.	INTERLAMINAR + 25% CORE
2	1-8-2-3	294.	12677.	4916.	INTERLAMINAR + 25% CORE
2	1-8-2-7	561.	10854.	4226.	CORE
2	1-8-2-8	561.	9942.	3854.	ADHESIVE
2	1-8-2-9	561.	10075.	3923.	ADHESIVE
2	1-8-2-10	561.	9630.	3806.	ADHESIVE

* SPECIMEN BROKE DUE TO THERMAL STRESS

NOTES: ALL SPECIMEN CROSS SECTIONS MEASURE 50.8 MM BY 50.8 MM

ADHESIVE = ADHESIVE TO LAMINATE AT LOAD BLOCK
INTERLAMIANAR = INTERLAMINAR TENSION
CORE = CORE TO LAMINATE BOND FAILURE

FIBER VOLUME = 51.4 %

TABLE 5.5-2. CONCLUDED

(b) U.S. CUSTOMARY UNITS

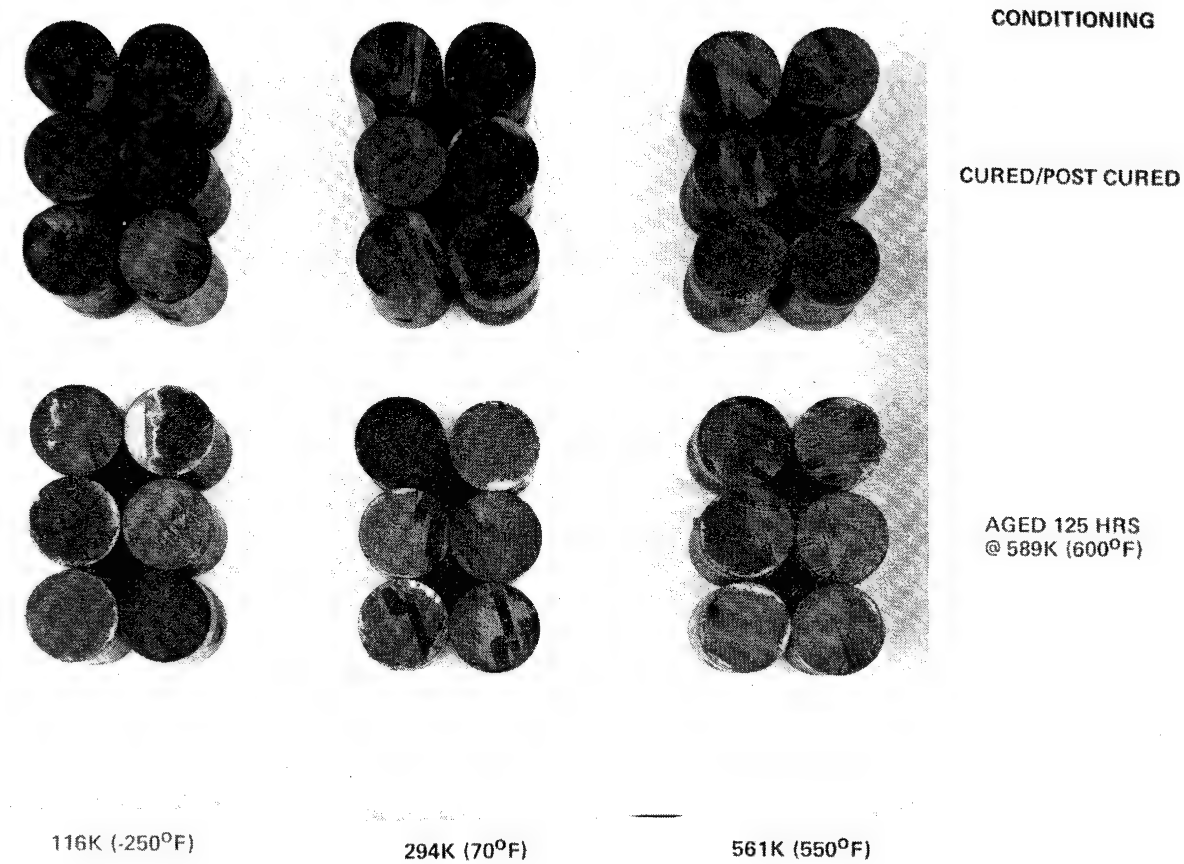
COND. CODE	SPECIMEN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS PSI	FAILURE MODE
1	1-8-1-4	-250.	*	*	INTERLAMINAR
1	1-8-1-5	-250.	1440.	360.	ADHESIVE
1	1-8-1-6	-250.	630.	158.	ADHESIVE
1	1-8-1-1	70.	3825.	956.	INTERLAMINAR
1	1-8-1-2	70.	3945.	986.	INTERLAMINAR + 25% CORE
1	1-8-1-3	70.	3075.	769.	INTERLAMINAR
1	1-8-1-7	550.	1775.	455.	ADHESIVE
1	1-8-1-8	550.	1435.	368.	ADHESIVE
1	1-8-1-9	550.	1005.	251.	ADHESIVE
1	1-8-1-10	550.	1475.	369.	ADHESIVE
2	1-8-2-4	-250.	*	*	INTERLAMINAR
2	1-8-2-5	-250.	*	*	INTERLAMINAR
2	1-8-2-6	-250.	*	*	INTERLAMINAR
2	1-8-2-1	70.	2950.	741.	INTERLAMINAR
2	1-8-2-2	70.	2975.	744.	INTERLAMINAR + 25% CORE
2	1-8-2-3	70.	2850.	713.	INTERLAMINAR + 25% CORE
2	1-8-2-7	550.	2440.	613.	CORE
2	1-8-2-8	550.	2235.	559.	ADHESIVE
2	1-8-2-9	550.	2265.	569.	ADHESIVE
2	1-8-2-10	550.	2165.	552.	ADHESIVE

* SPECIMEN BROKE DUE TO THERMAL STRESS

NOTES: ALL SPECIMEN CROSS SECTIONS MEASURE 2 IN BY 2 IN

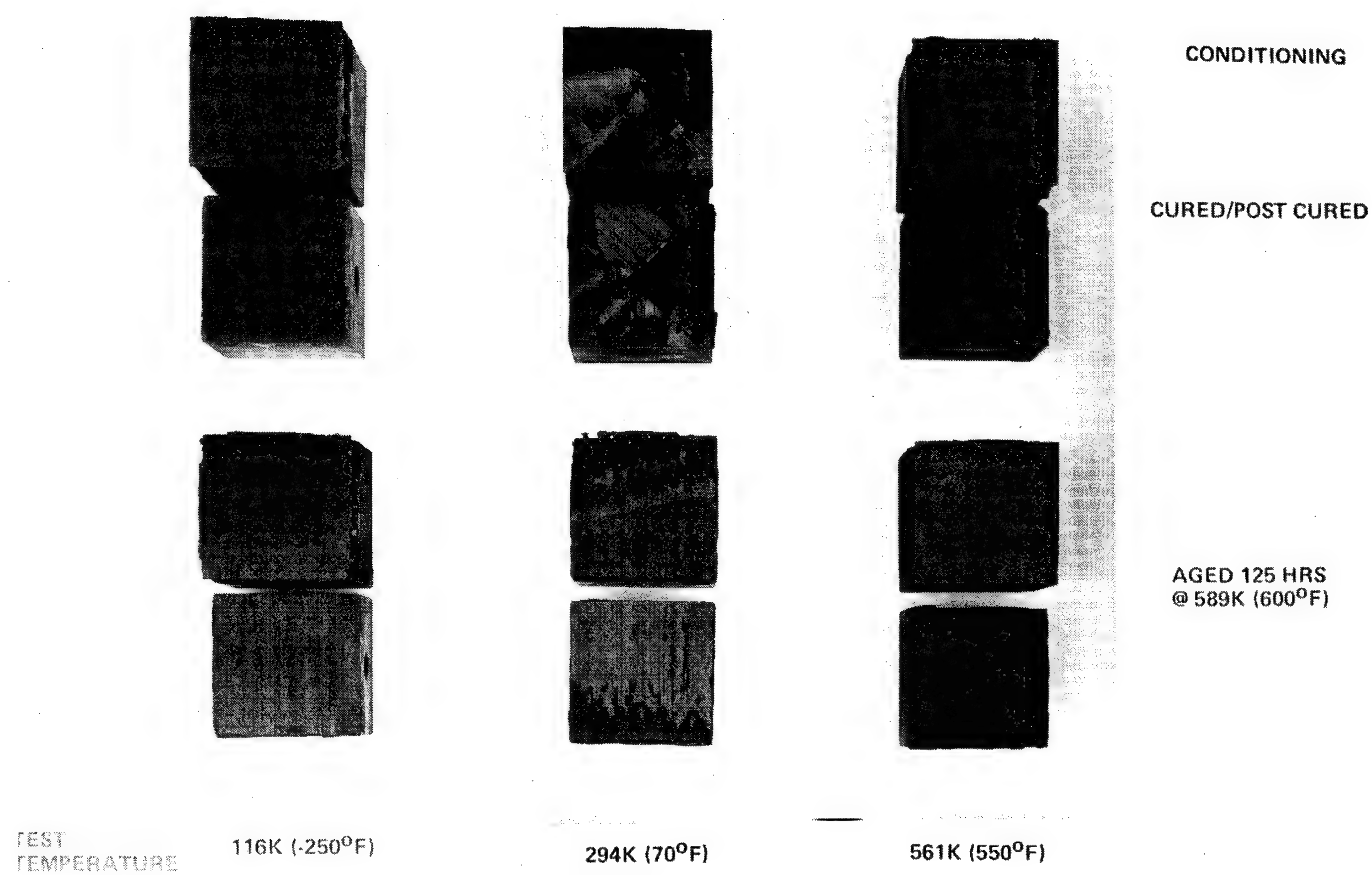
ADHESIVE = ADHESIVE TO LAMINATE AT LOAD BLOCK
INTERLAMIANAR = INTERLAMINAR TENSION
CORE = CORE TO LAMINATE BOND FAILURE

FIBER VOLUME = 51.4 %



Failed Specimens — Flatwise Tension-Laminate
Celion 3000/PMR-15 $[0/\pm45/90]_{2S}$
Matrix 1 Test 7

Figure 5.5-3: Celion 3000/PMR-15 Flatwise Laminate-to-Laminate Tension Tests $[0/\pm45/90]_{2S}$ Layup - Failed Specimens



Failed Specimens — Flatwise Tension Laminate/Core
Celion 3000/PMR-15 $[0/\pm45/90]_{2S}$
Matrix 1 Test 8

Figure 5.5-4: Celion 3000/PMR-15 Flatwise Laminate-to-Core Tension Tests $[0/\pm45/90]_{2S}$ Layup - Failed Specimens

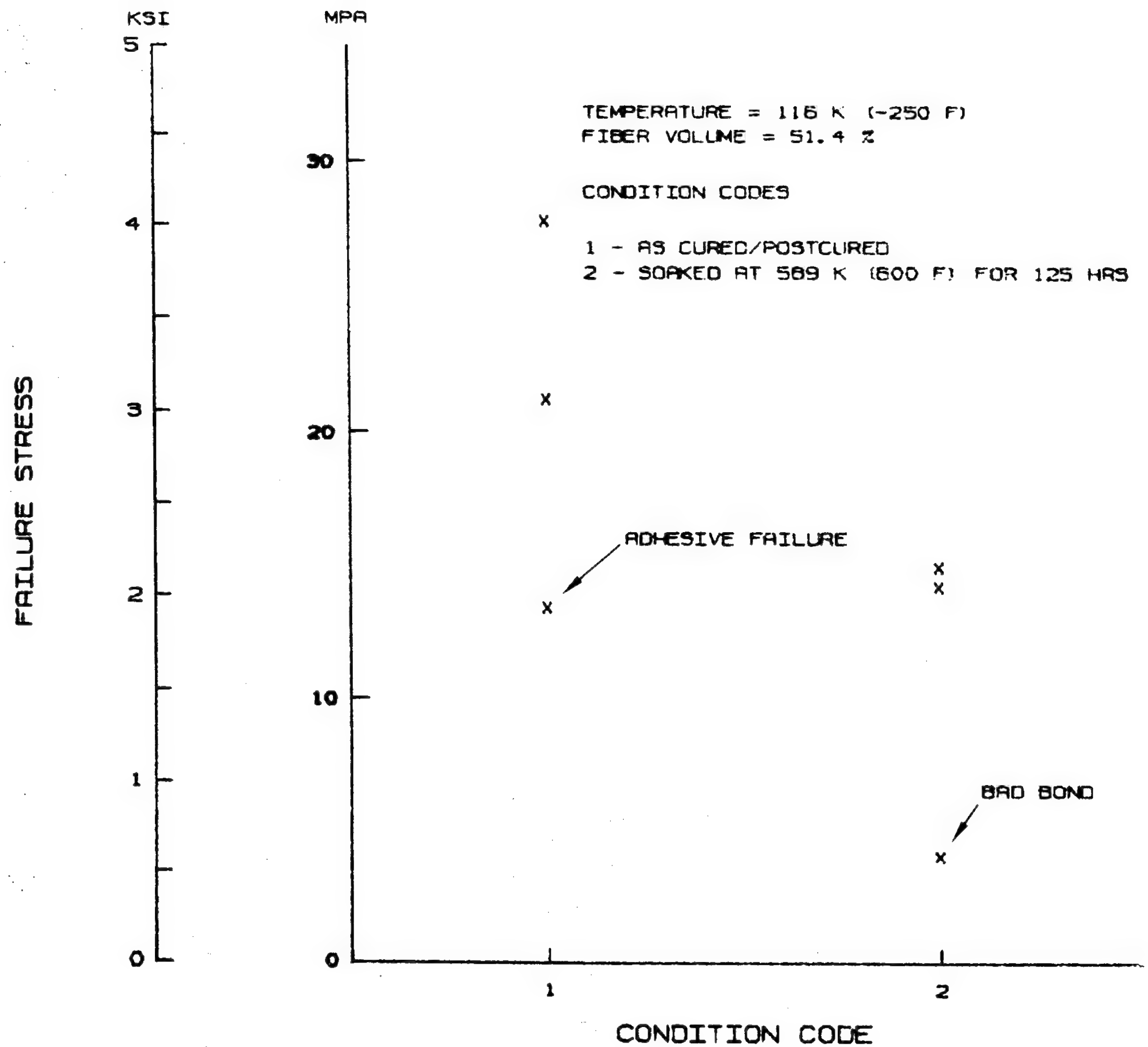


Figure 5.5-5: Celion 3000/PMR-15 Flatwise Laminate to Laminate Tests $(0/+45/90)_{2S}$ Layup 116K (-250^{o}F)

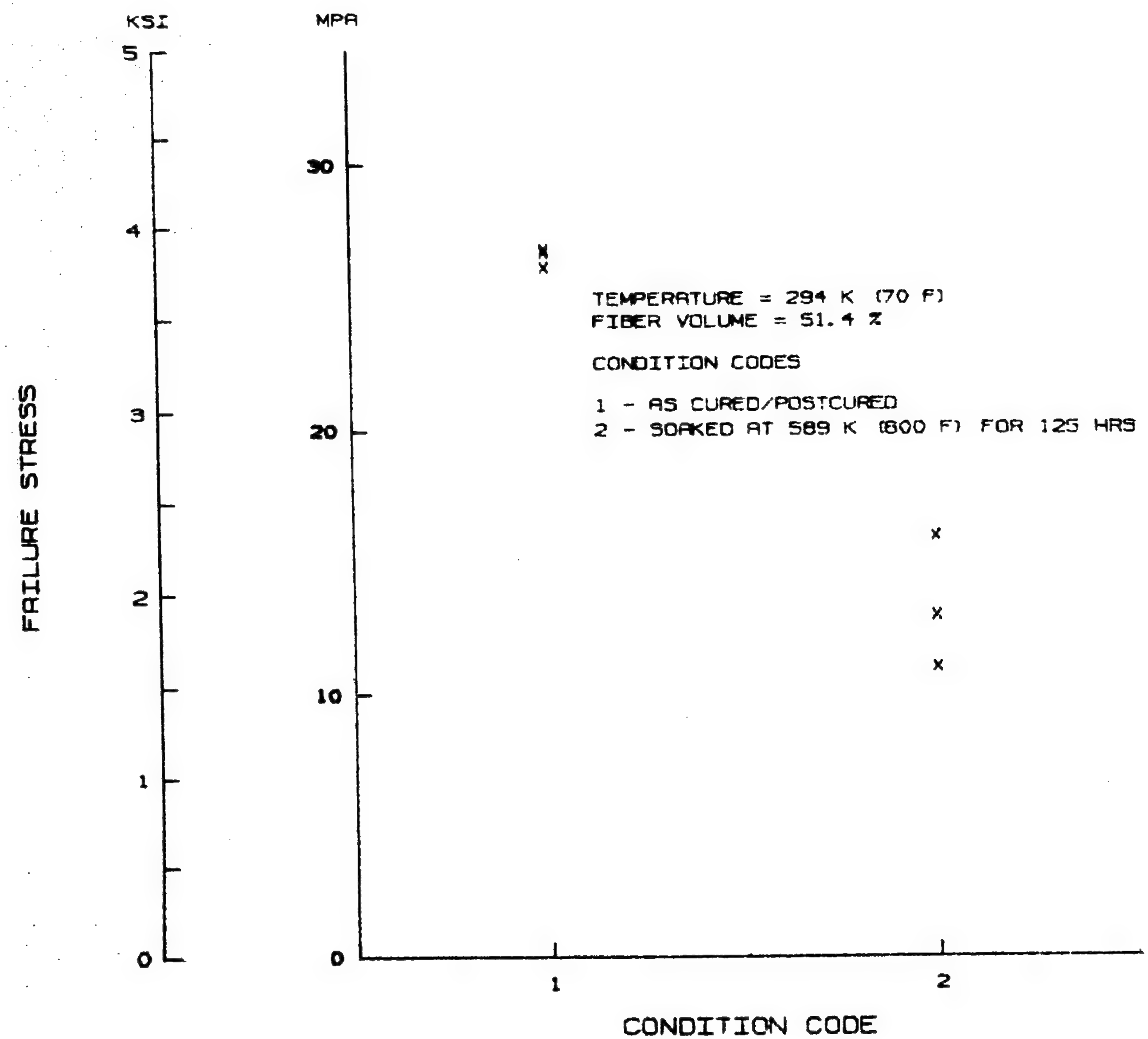


Figure 5.5-6: Celion 3000/PMR-15 Flatwise Laminate to Laminate Tests $(0/\underline{+}45/90)_{2S}$ Layup 294K (70^{o}F)

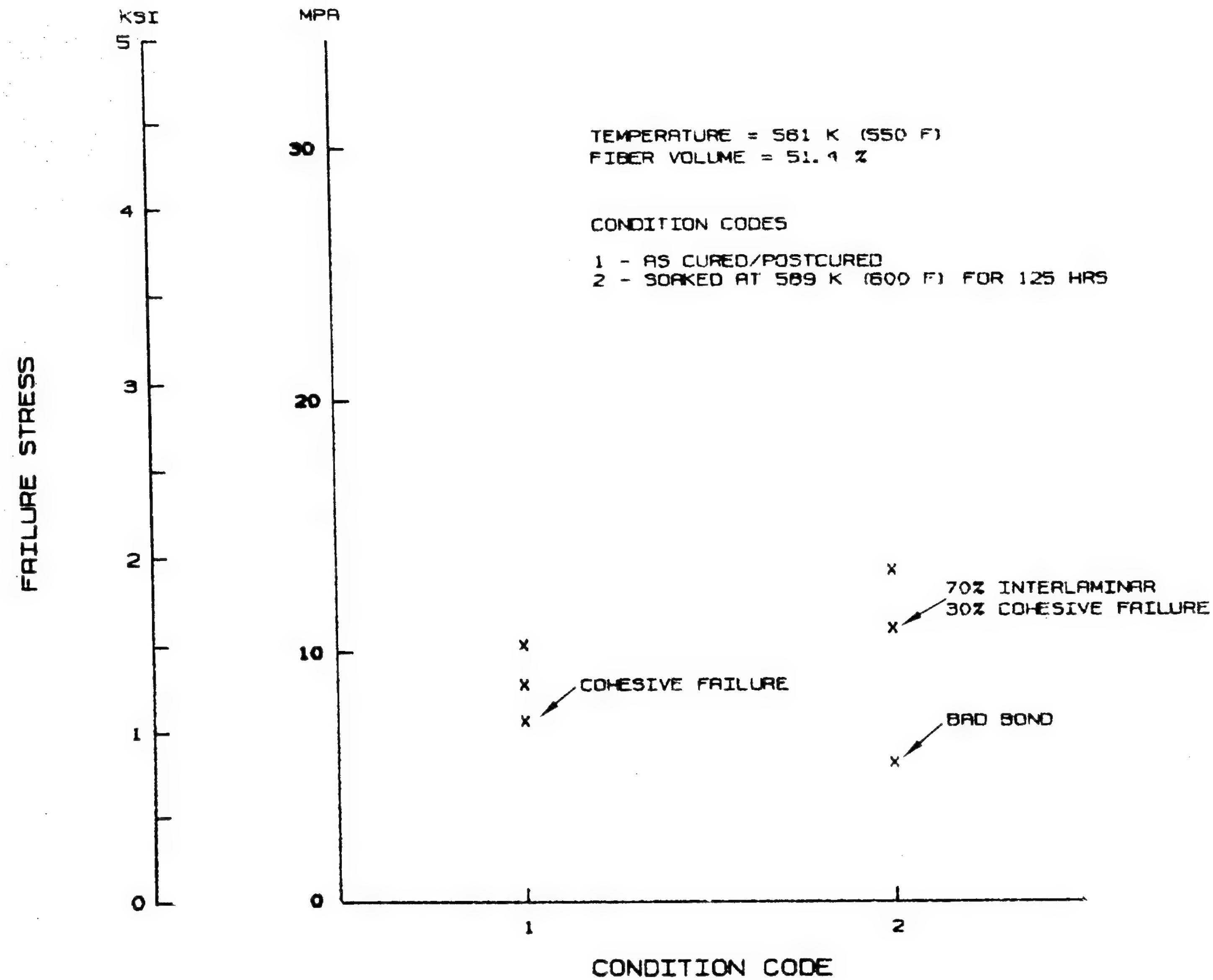


Figure 5.5-7: Celion 3000/PMR-15 Flatwise Laminate to Laminate Tests $(0/\pm45/90)_{2S}$ Layup 561K (550^{O}F)

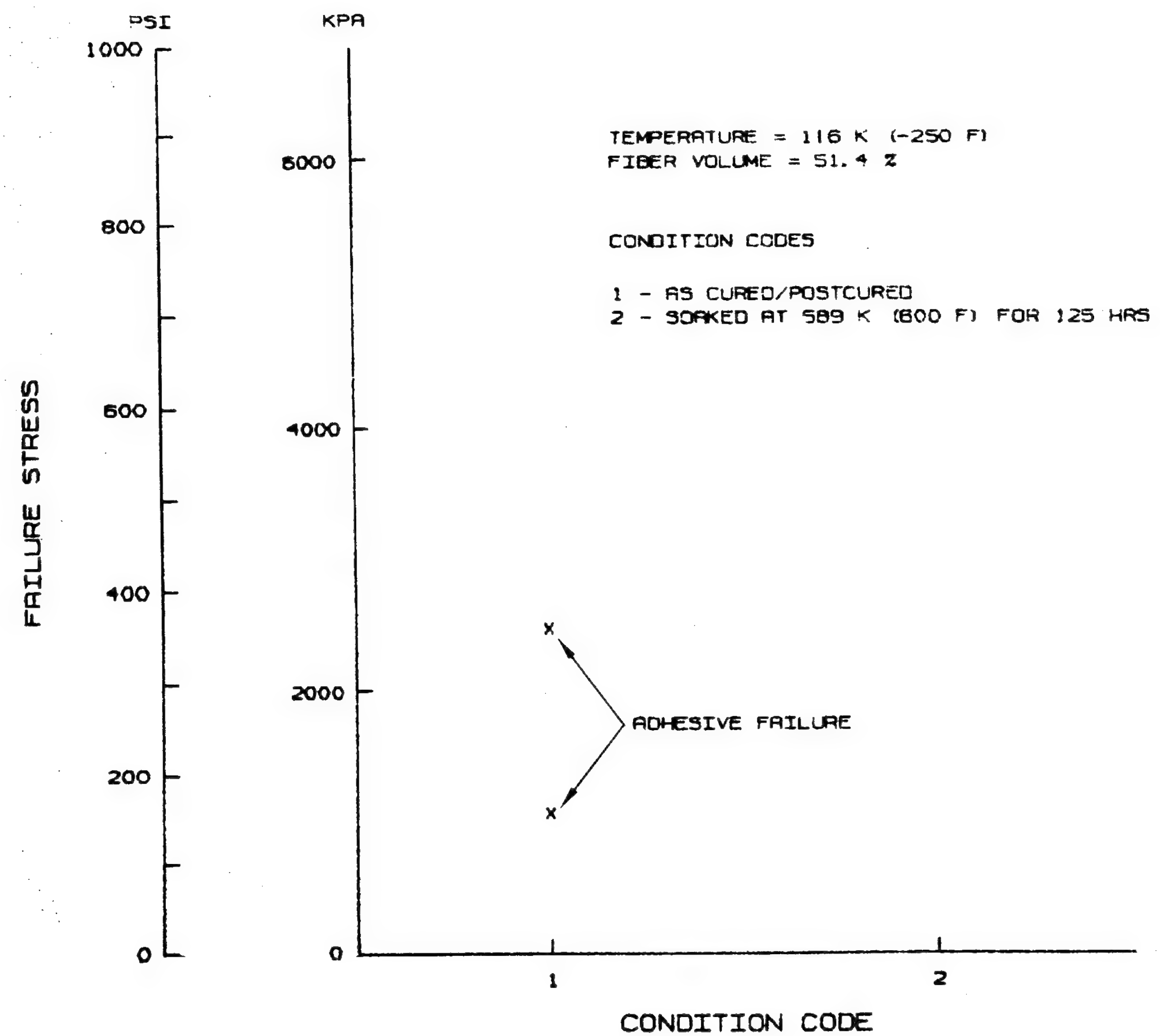


Figure 5.5-8: Celion 3000/PMR-15 Flatwise Laminate to Core Tests $(0/\underline{+}45/90)_{2S}$ Layup 116K ($-250^{o}F$)

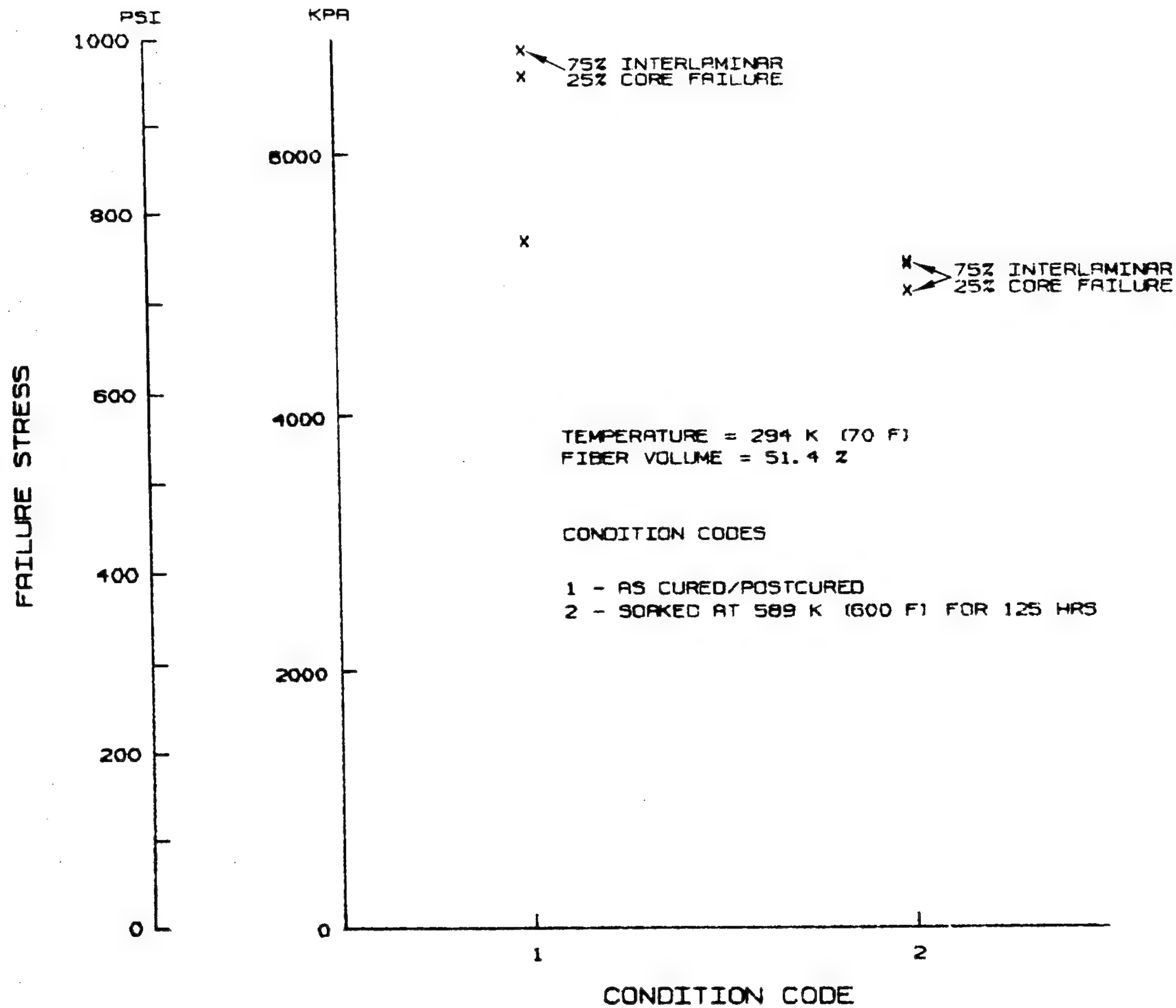


Figure 5.5-9: Celion 3000/PMR-15 Flatwise Laminate to Core Tests $(0/\pm45/90)_{2S}$ Layup 294K (70^{o}F)

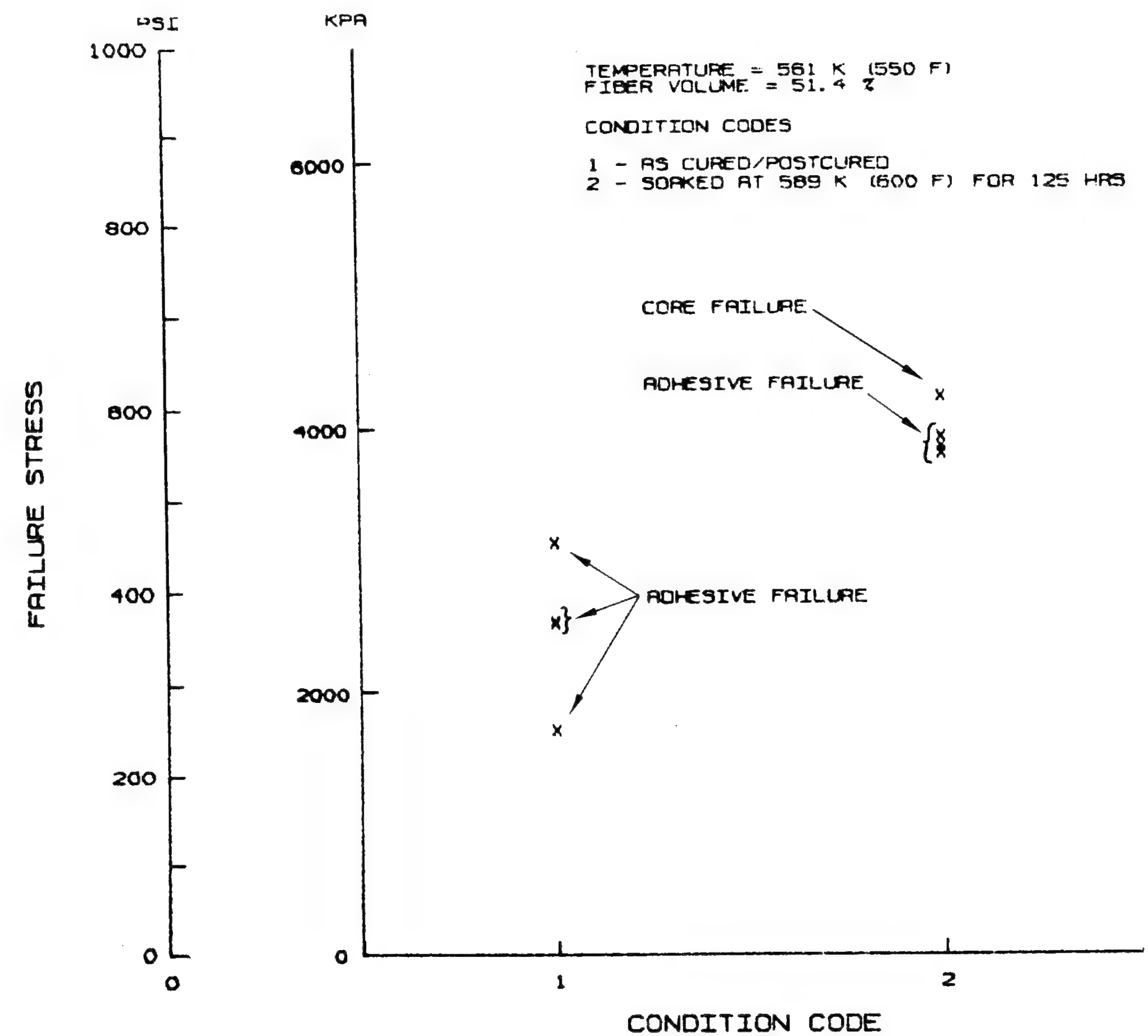


Figure 5.5-10: Celion 3000/PMR-15 Flatwise Laminate to Core Tests $(0/\pm 45/90)_{2S}$ Layup 561K (550^{o}F)

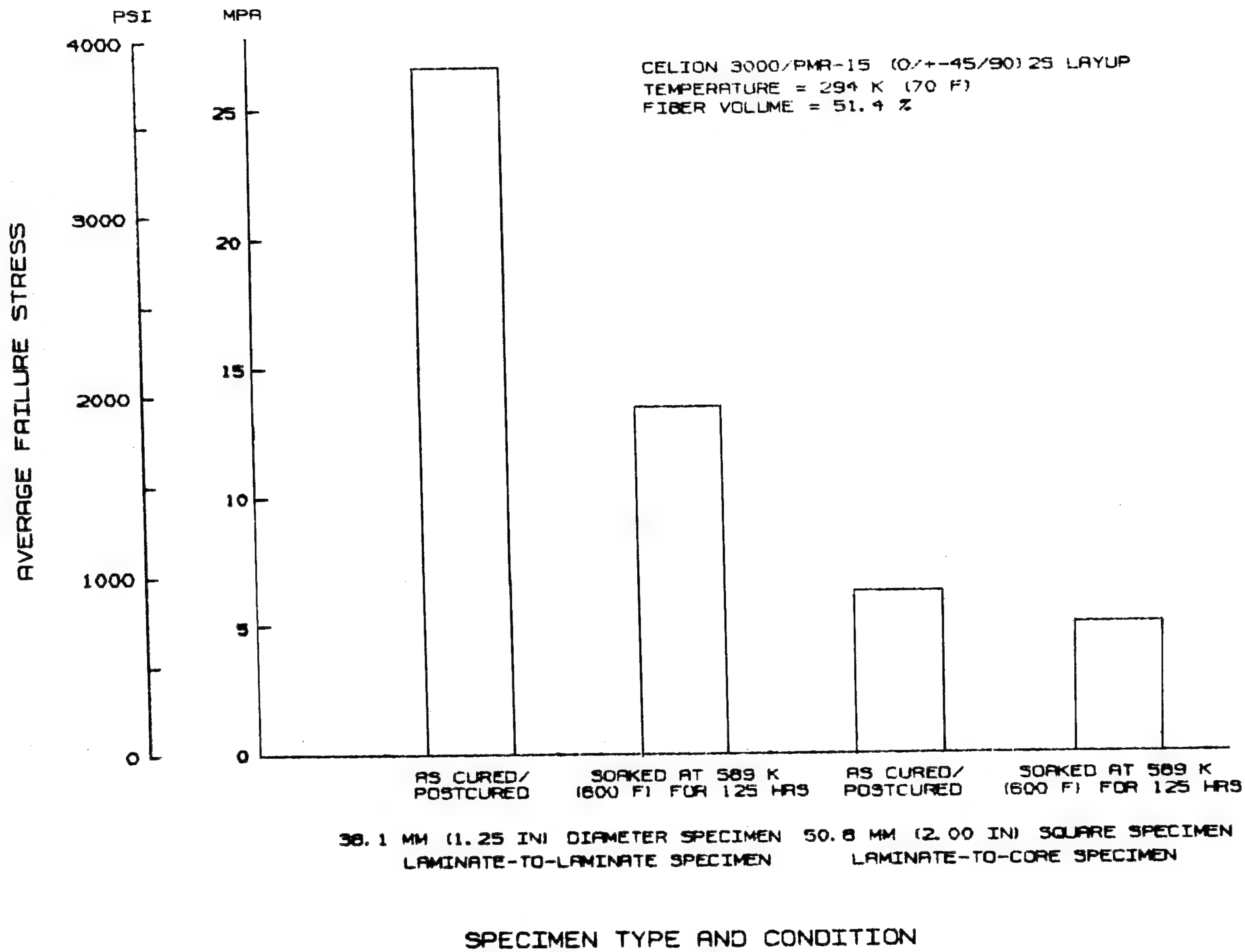


Figure 5.5-11: Comparison of Interlaminar Tension Strength Celion 3000/PMR-15 $(0/\underline{+}45/90)_{2S}$ Layup

5.6 Rail Shear Tests

This section presents test procedures and test results for rail shear tests of a $(\pm 45)_{3S}$ laminate. Test results also include shear modulus calculations based on the tension tests of $(0/\pm 45/90)_{4S}$ and $(\pm 45)_{8S}$ laminates presented in Section 5.3.

5.6.1 Test Procedures

Rail shear tests (test 13 of Matrix 1) were conducted using procedures in Reference 1. Bonded and tapered titanium rails, provided by NASA LaRC, were used for load introduction. A typical test set up is shown in Figure 5.6-1. After conditioning, specimens were installed in a Baldwin Universal test machine. Strain gages were connected to an x-y plotter. Load was applied at a cross head speed of 2.1×10^{-5} m/sec (.05 in/min) until failure.

5.6.2 Test Results

Test results are summarized in Table 5.6-1. Typical failed specimens are shown in Figure 5.6-2.

Test results are plotted as a function of temperature and conditioning in Figures 5.6-3 through 5.6-6. All data have been plotted; however, as noted in Table 5.6-1, several of the specimens had failures in the grip area. Failure stresses shown in Table 5.6-1 are probably lower than actual ultimates for those specimens that failed in the grip area; however, modulus data should be valid since they are based on initial slopes of the stress-strain curves. Laminate shear modulus data compare very well with values predicted using uniaxial material properties from the other design allowable tests. Predicted G_{XY} values were 36.7 GPa (5.33×10^6 psi) and 36.4 GPa (5.28×10^6 psi) at room temperature and 561K (550°F) respectively as

compared to average measured values of 40.5 GPa (5.88×10^6 psi) and 33.3 GPa (4.83×10^6 psi) respectively for aged specimens.

In addition the in-plane lamina shear modulus in the principal fiber direction, G_{12}, was obtained from strain gage data from the tension tests of the $\pm 45_{8S}$ laminate discussed in Section 5.3. In-plane shear modulus, Gxy, of a $(0/\pm 45/90)_S$ laminate was calculated from the tension tests of the $(0/\pm 45/90)_{4S}$ laminates. Calculations were made using the procedure of Rosen and Petit in Ref. (2). Values for the shear modulus are given in Table 5.6-2. There was no significant change due to temperature in Gxy for the $(0/\pm 45/90)_{4S}$ laminate. Elevated temperature produced a 38% drop in the single lamina in-plane shear modulus, G_{12}.

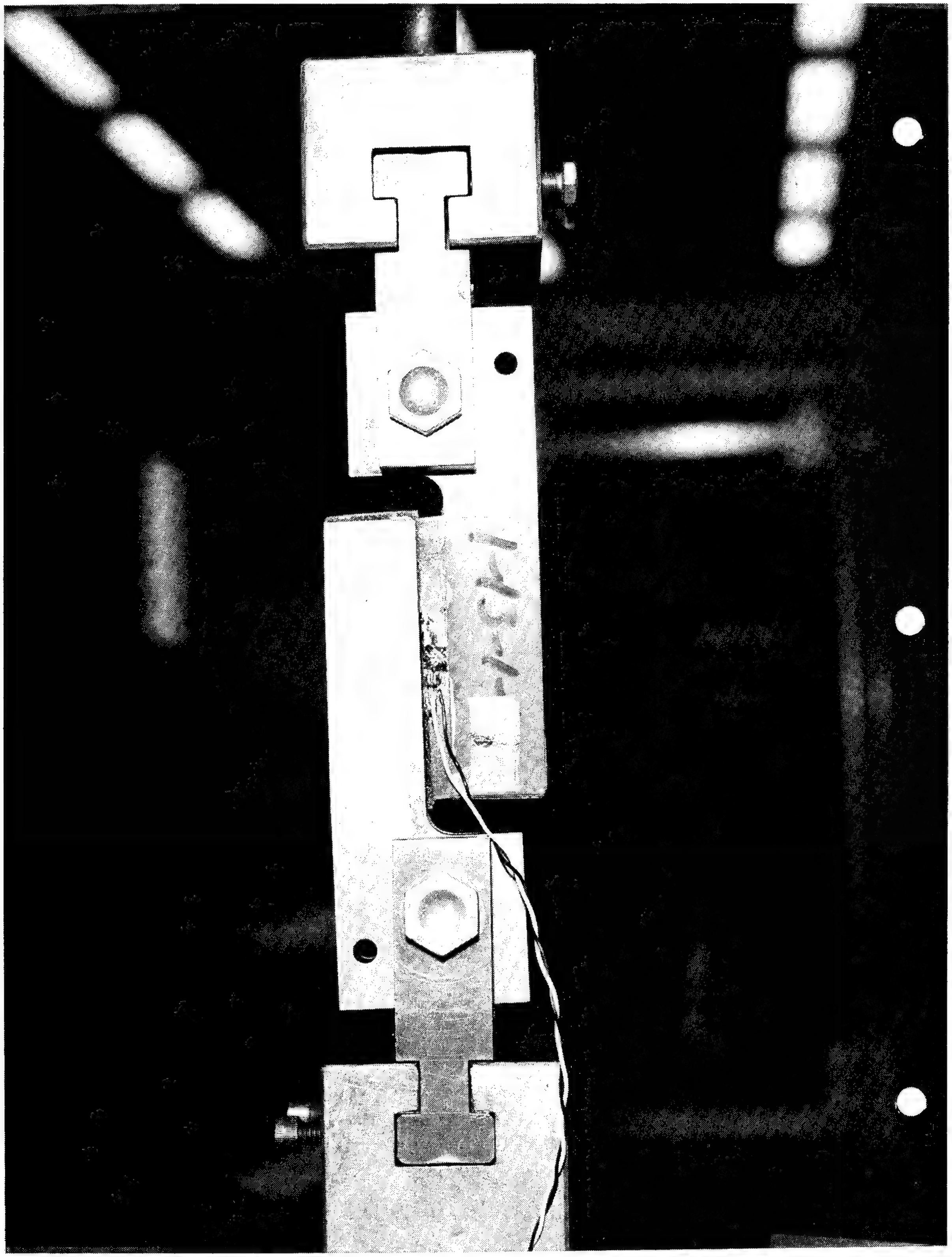


Figure 5.6-1: Celion 3000/PMR-15 Design Allowables In-Plane Shear Test Setup

TABLE 5.6-1. CELION 3000/PMR-15 DESIGN ALLOWABLES IN-PLANE SHEAR TESTS [+-45]3S LAYUP

(a) SI UNITS

COND. CODE	SPECIMEN	LENGTH MM	DIST. BETWEEN RAILS MM	THK MM	TEST TEMP. K	FAILURE LOAD N	FAILURE STRESS MPA	STRAIN GAGE DATA SHEAR MODULUS GPA	FAILURE MODE
1	1-13-1-1	76.07	6.3	0.737	294.	7784.	139.	NO DATA	BOND
1	1-13-1-2	76.07	7.1	0.698	294.	23620.	447.	41.1	SHEAR AND INTERLAMINAR IN GRIP AREA
1	1-13-1-3	76.07	7.4	0.711	294.	20996.	387.	38.0	SHEAR AND INTERLAMINAR IN GRIP AREA
1	1-13-1-4	76.20	8.1	0.711	561.	20306.	374.	47.2	SHEAR
1	1-13-1-5	76.20	7.1	0.698	561.	17326.	323.	30.5	SHEAR
1	1-13-1-6	76.20	7.6	0.711	561.	15769.	291.	44.0	SHEAR
2	1-13-2-7	76.20	NO DATA	0.787	294.	21396.	356.	41.0	INTERLAMINAR IN GRIP AREA
2	1-13-2-8	76.33	7.4	0.737	294.	20195.	360.	40.1	INTERLAMINAR IN GRIP AREA
2	1-13-2-9	76.20	7.4	0.724	561.	12322.	222.	32.5	BOND
2	1-13-2-10	76.20	7.9	0.698	561.	13789.	257.	34.2	BOND

NOTE: FIBER VOLUME = 51.4 %

(b) U.S. CUSTOMARY UNITS

COND. CODE	SPECIMEN	LENGTH IN	DIST. BETWEEN RAILS IN	THK IN	TEST TEMP. F	FAILURE LOAD LBS	FAILURE STRESS KSI	STRAIN GAGE DATA SHEAR MODULUS MSI	FAILURE MODE
1	1-13-1-1	2.995	.25	.0290	70.	1750.	20.1	NO.DATA	BOND
1	1-13-1-2	2.995	.28	.0275	70.	5310.	64.8	5.96	SHEAR AND INTERLAMINAR IN GRIP AREA
1	1-13-1-3	2.995	.29	.0280	70.	4720.	56.2	5.51	SHEAR AND INTERLAMINAR IN GRIP AREA
1	1-13-1-4	3.000	.32	.0280	550.	4565.	54.3	6.84	SHEAR
1	1-13-1-5	3.000	.28	.0275	550.	3895.	46.9	4.43	SHEAR
1	1-13-1-6	3.000	.30	.0280	550.	3545.	42.2	6.38	SHEAR
2	1-13-2-7	3.000	NO DATA	.0310	70.	4810.	51.7	5.94	INTERLAMINAR IN GRIP AREA
2	1-13-2-8	3.005	.29	.0290	70.	4540.	52.2	5.81	INTERLAMINAR IN GRIP AREA
2	1-13-2-9	3.000	.29	.0285	550.	2770.	32.2	4.71	BOND
2	1-13-2-10	3.000	.31	.0275	550.	3100.	37.3	4.96	BOND

NOTE: FIBER VOLUME = 51.4 %

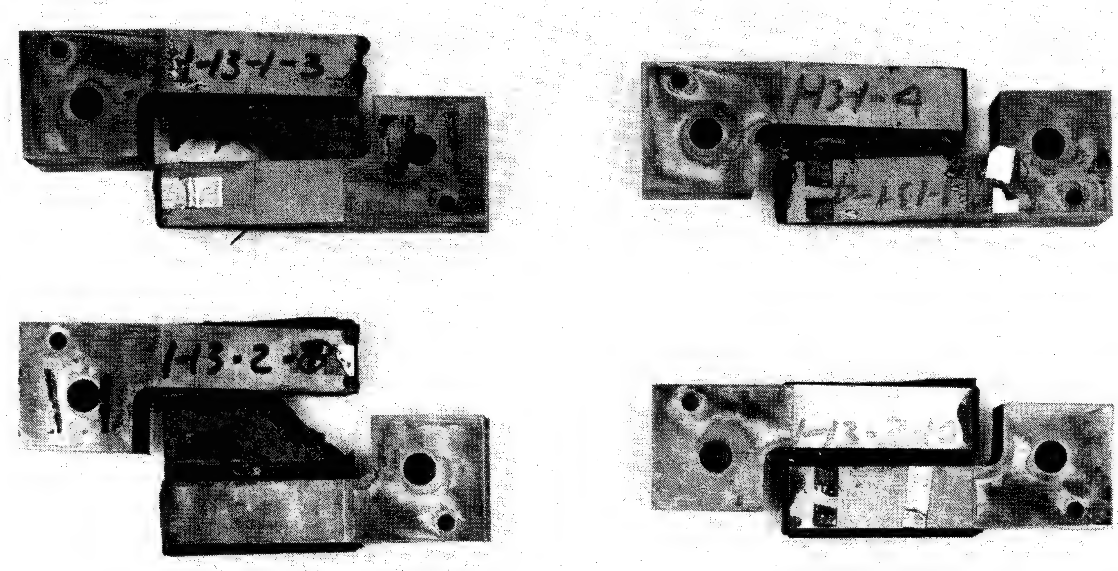


Figure 5.6-2: Celion 3000/PMR-15 In-Plane Shear Tests $[\underline{+}45]_{3S}$ Layup - Failed Specimens

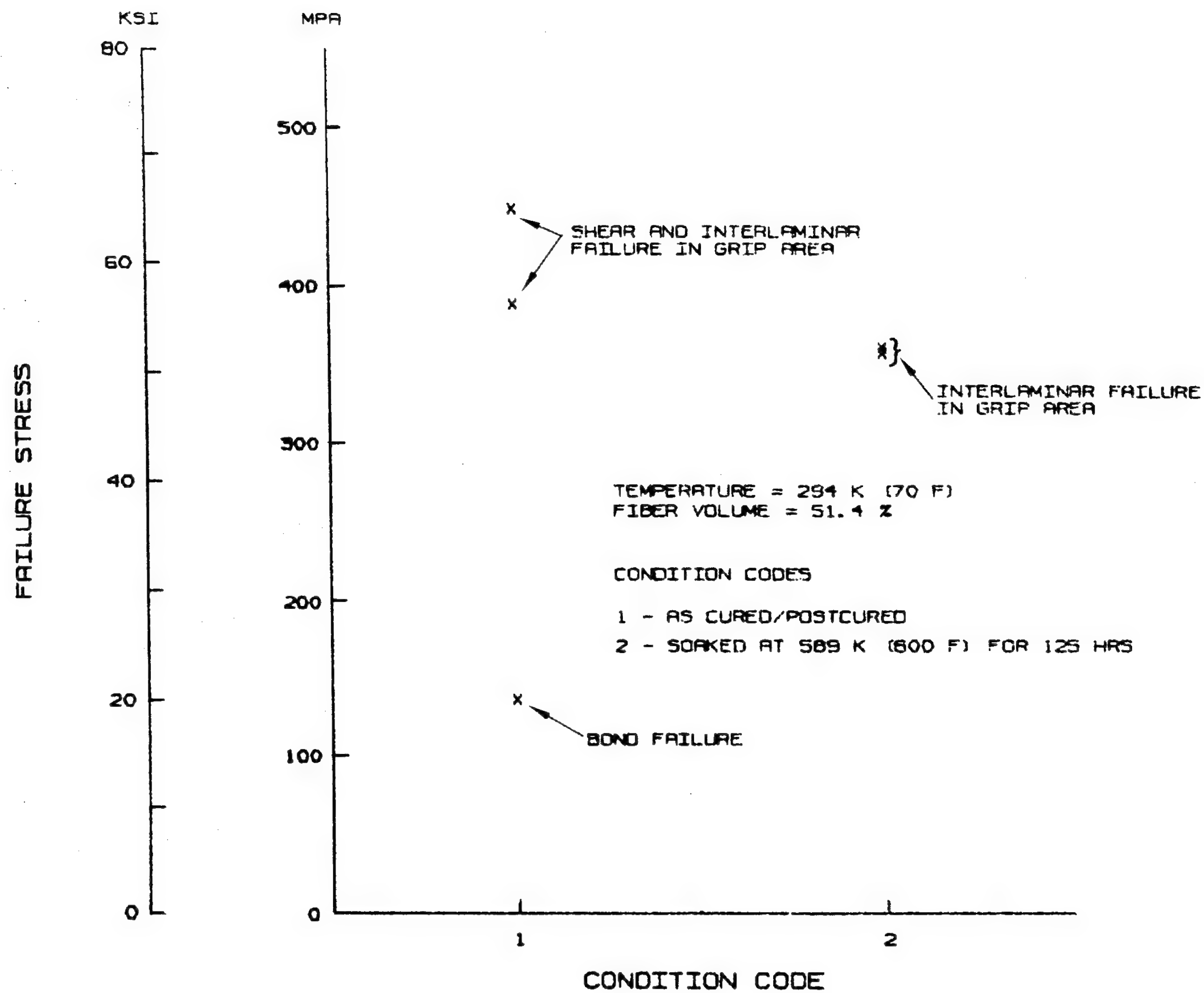


Figure 5.6-3: Celion 3000/PMR-15 In-Plane Shear Tests $(\underline{+}45)_{3S}$ Layup 294K (70^{0}F) - Failure Stress

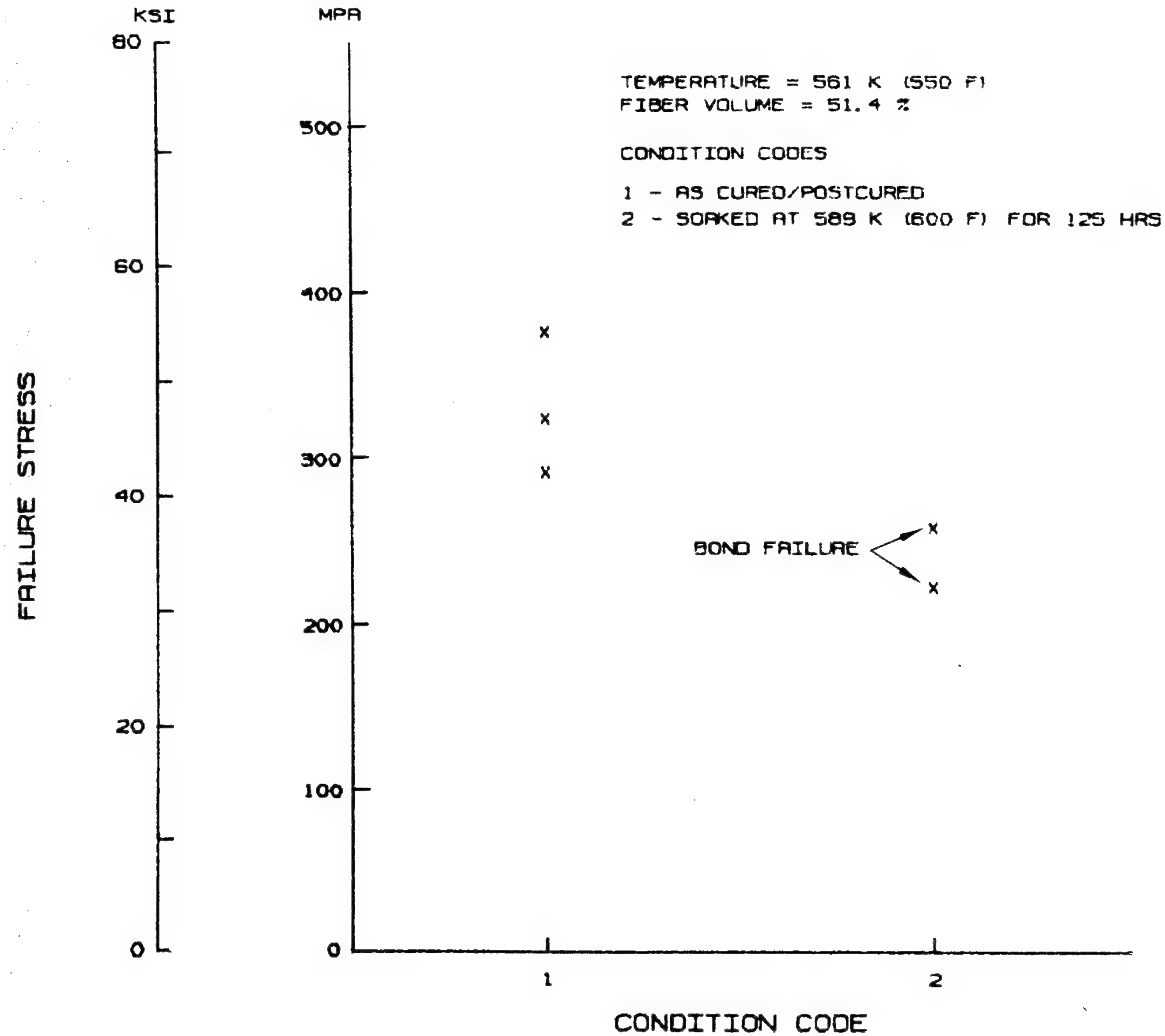


Figure 5.6-4: Celion 3000/PMR-15 In-Plane Shear Tests $(\pm 45)_{3S}$ Layup 561K (550^{o}F) - Failure Stress

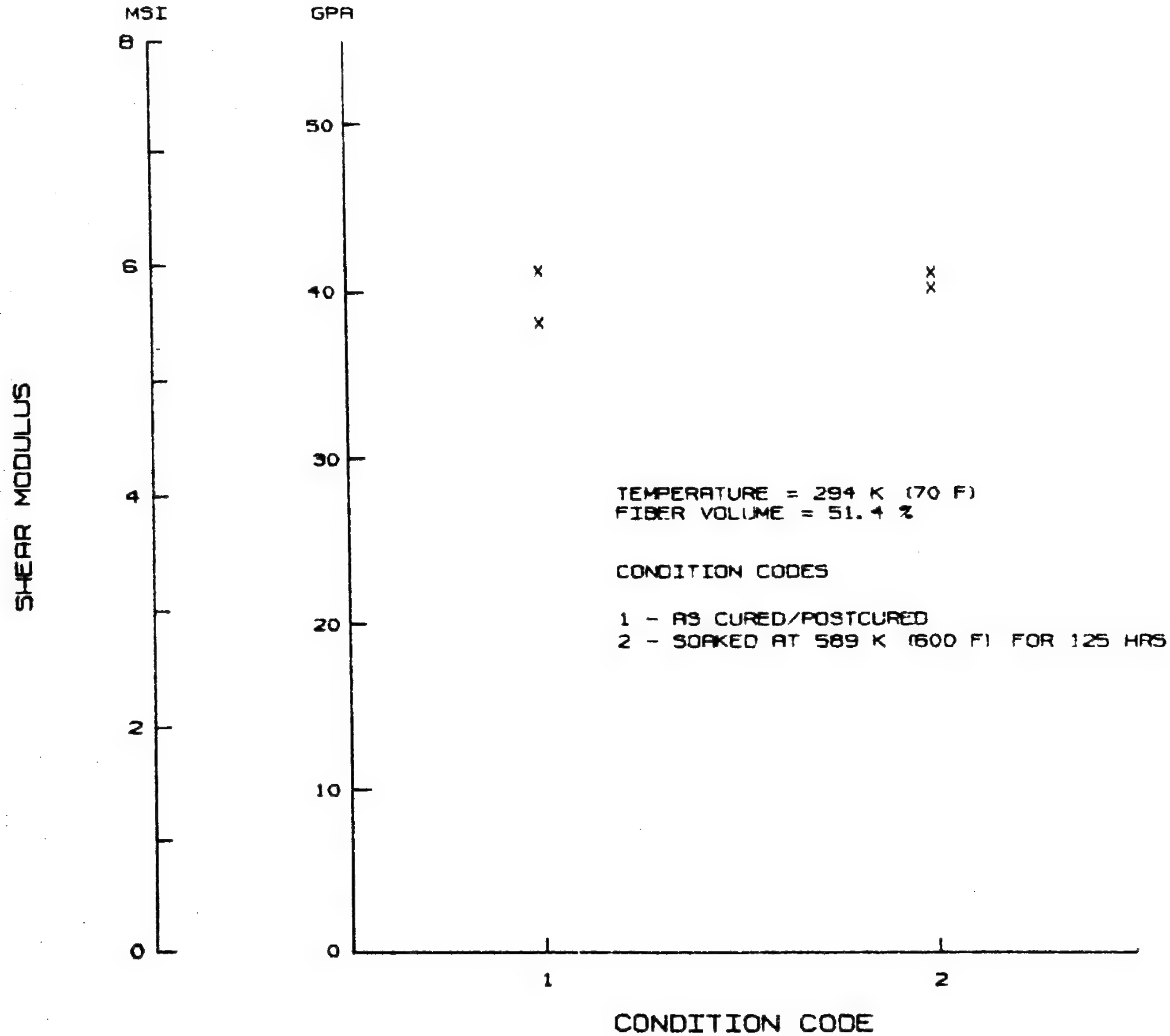


Figure 5.6-5: Celion 3000/PMR-15 In-Plane Shear Tests $(\pm 45)_{3S}$ Layup 294K (70^{0}F) - Modulus

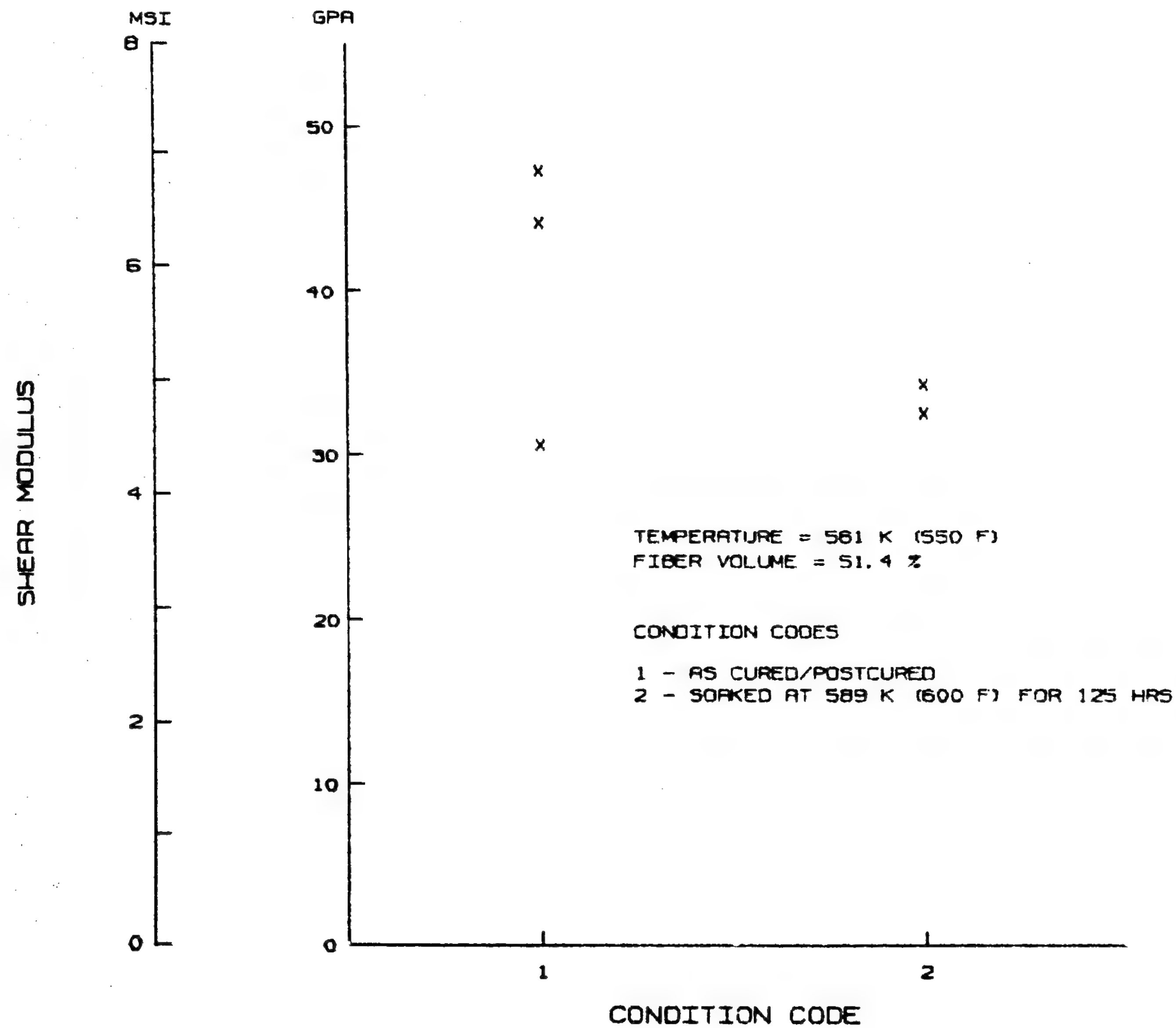


Figure 5.6-6: Celion 3000/PMR-15 In-Plane Shear Tests $(\pm 45)_{3S}$ Layup 561K (550^{o}F) - Modulus

Table 5.6-2: In-Plane Shear Modulus Data Calculated From Tensile Tests Celion 3000/PMR-15

LAMINATE LAYUP	CONDITION CODE	TEMPERATURE K °F	G_{xy} GPa 10^6 psi	G_{12} GPa 10^6 psi
$\pm 45_{8S}$	2	294 (70)	——	4.41 (.64)
	3	294 (70)	——	4.07 (.59)
	4	294 (70)	——	4.34 (.63)
	2	561 (550)	——	2.76 (.40)
$(0/\pm 45/90)_S$	3	294 (70)	17.4 (2.53)	——
	3	561 (550)	17.7 (2.57)	——

NOTE: Fiber Volume = 51.4%

5.7 Coefficient of Thermal Expansion (CTE) Test

This section presents test procedures and test results for CTE tests of $(0/\pm45/90)_{4S}$, $(0/\pm45/90)_{2S}$ and $(\pm45)_{8S}$ laminates and of A7F adhesive.

5.7.1 Test Procedures

Coefficient of thermal expansion (CTE) measurements were made using a Thermo- Physic Corp. Model TE-3000A dilatometer. The thermal expansion sample is placed in a quartz tube with a movable quartz rod. A thermocouple is connected to the sample and the expansion as a function of temperature change is determined.

5.7.2 Test Results

Test results are summarized in Tables 5.7-1 and 5.7-2 respectively. Because of laminate symmetry, expansion in the y-direction is equal to that in the x-direction. Laminate data have been corrected for the CTE of fused quartz.

Test results for the laminate are in the range expected and do not indicate any significant change due to the various environmental conditions evaluated. Data for the adhesive, however, show a significant reduction in CTE due to aging.

Table 5.7-1: CTE DATA: CELION 3000/PMR-15

Specimen No.	Laminate	Condition*	Test Axis	CTE, m/m-K$\times 10^{-6}$ (in/in^{o}F$\times 10^{-6}$) 116K to RT (-250F)	RT to 589K (600^{o}F)	116K to 589K (-250^{o}F) (600^{o}F)
2W4582-15D1	$(0/\pm 45/90)_{4S}$	2	X	2.13 (1.18)	2.65 (1.47)	2.45 (1.36)
2W4582-15D3	$(0/\pm 45/90)_{4S}$	2	X	2.17 (1.2)	2.79 (1.55)	2.55 (1.42)
2W4582-15C2	$(0/\pm 45/90)_{4S}$	1	X	2.14 (1.19)	2.55 (1.42)	2.39 (1.33)
2W4582-10B	$(\pm 45)_{8S}$	2	Z		52.9 (29.4)	
2W4582-7C	$(0/\pm 45/90)_{2S}$	3	Z		48.1 (26.7)	
2W4582-13B	$(\pm 45/90/0)_{4S}$	3	Z		37.7 (20.9)	
2W4582-14B	$(0/\pm 45/90)_{4S}$	2	Z		48.5 (26.9)	
2W4582-14	$(0/\pm 45/90)_{4S}$	1	Z		54.7 (30.4)	
2W4582-10	$(\pm 45)_{8S}$	1	Z		54.1 (30.1)	

* 1 = as cured/postcured, 2 = aged 125 hrs @589K (600^{o}F), 3 = 125 thermal cycles

Table 5.7-2 CTE DATA: A7F Adhesive (LARC 13 Amide-Imide Modified)

Conditioning	Average Temperature K (^{o}F)	CTE mm/mm-K x 10^{-6} (in/in-^{o}F$\times 10^{-6}$)
Cured/Post Cured	279 (43)	26.6 (14.8)
	385 (234)	30.3 (16.8)
	483 (410)	35.4 (19.7)
Aged	363 (194)	17.5 (9.7)
	471 (388)	20.8 (11.6)

5.8 Data Summary

This section presents summaries of all the test results, except CTE data, for Celion 3000/PMR-15. Data shown are test type, laminate lay-up, temperature, conditioning code, number of specimens, average test results and coefficient of variation. Tension, compression and rail shear tests are summarized in Tables 5.8-1 through 5.8-3. Flatwise (out-of-plane) tension tests are summarized in Tables 5.8-4.

Test data show very consistent results in that coefficients of variations are generally very small and within ranges normally experienced in composite testing. The few exceptions are due to small sample size or explainable test anomalies. Average test results shown can be used for preliminary design and sizing of graphite/polyimide composite structure.

Table 5.8-1: Summary of Tension Tests--Celion 3000/PMR-15, Fiber Volume = 51.4%

TEST TYPE	LAYUP	COND. CODE	TEMPERATURE K	TEMPERATURE °F	NO. OF SPEC.	AVERAGE STRESS MPa	AVERAGE STRESS Ksi	AVERAGE STRESS [1]	FAILURE STRAIN	FAILURE STRAIN [1]	EXTENSOMETER MODULUS GPa	EXTENSOMETER MODULUS Msi	EXTENSOMETER MODULUS [1]	STRAIN GAGE MODULUS GPa	STRAIN GAGE MODULUS Msi	POISSON'S RATIO
TENSION	$(0)_{16}$	1	294	70	3	1278	185.3	.029	.0106	.065	122.9	17.82	.049			
		1	561	550	3	1302	188.8	.047	.0109	.093	125.5	18.20	.057			
		2	294	70	3	1287	186.6	.072	.0098	.054	129.5	18.79	.074			
		2	561	550	2	1129	163.7	.029	.0085	.116	133.1	19.30	.021			
		3	294	70	5	1238	179.5	.036	.0097	.054	126.5	18.35	.045	129.6*	18.80	.3272*
		3	561	550	5	1188	172.3	.039	.0097	.053	125.9	18.25	.048	150.7*	21.85	.4013*
TENSION	$(90)_{30}$	1	294	70	3	47.02	6.820	.022	.0060	.252	8.18	1.19	.049			
		1	561	550	3	19.99	2.900	.130	.0036	.200	5.72	.83	.042			
		2	294	70	3	45.37	6.580	.094	.0057	.113	8.37	1.21	.024			
		2	561	550	3	17.88	2.593	.093	.0034	.147	5.61	.81	.111			
		3	294	70	5	41.59	6.032	.094	.0055	.105	7.80	1.13	.035	8.62*	1.25	.0320*
		3	561	550	5	15.24	2.210	.047	.0034	.278	5.41	.78	.149	6.21*	.90	.0176*
		4	294	70	3	42.86	6.217	.064	.0053	.078	7.33	1.06	.005			
		4	561	550	3	7.65	1.109	.076	.0026	-	2.73	.40	.124			
TENSION	$(0/\pm45/90)_{4S}$	1	294	70	3	508.6	73.77	.293	.0108	.059	49.1	7.13	.041			
		1	561	550	3	481.7	69.87	.068	.0112	.006	44.4	6.45	.010			
		2	294	70	3	477.3	69.23	.022	.0097	.015	50.1	7.27	.021			
		2	561	550	3	452.1	65.57	.029	.0101	.054	45.8	6.64	.095			
		3	294	70	5	400.6	58.10	.041	.0098	.062	45.2	6.55	.045	46.4*	6.74	.3280*
		3	561	550	5	375.9	54.52	.058	.0090	.111	45.7	6.63	.103	47.7*	6.92	.3477*
		4	561	550	5	370.4	53.72	.046	.0094	.047	39.4	5.72	.010			
TENSION	$(\pm45)_{8S}$	1	294	70	3	202	29.4	.024	No Data		14.5	2.11	.031			
		1	561	550	2	106	15.4	.064	.0430	-	8.0	1.16	.202			
		2	294	70	4	206	29.8	.043	No Data		14.5	2.10	.022	16.5**	2.40	.8690**
		2	561	550	4	100	14.6	.103	No Data		9.3	1.35	.094	10.1**	1.46	.8139**
		3	294	70	5	151	21.8	.111	.0172	-	13.1	1.89	.040	14.6*	2.12	.7851*
		3	561	550	5	110	16.0	.057	No Data		9.3	1.35	.120			
		4	294	70	3	227	33.0	.109	No Data		16.6	2.41	.141	15.6*	2.26	.7951
		4	561	550	3		Tab Failure		No Data		8.1	1.17	.107			

* 2 Specimens
** 1 Specimen

[1] Coefficient of Variation

Table 5.8-2: Summary of Compression Tests-Celion 3000/PMR-15, Fiber Volume = 51.4%

TEST TYPE	LAYUP	COND. CODE	TEMPERATURE K	TEMPERATURE °F	NO. OF SPEC.	AVERAGE STRESS MPa	AVERAGE STRESS Ksi	AVERAGE STRESS [1]	FAILURE STRAIN	FAILURE STRAIN [1]	EXTENSOMETER MODULUS GPa	EXTENSOMETER MODULUS Msi	EXTENSOMETER MODULUS [1]	STRAIN GAGE MODULUS GPa	STRAIN GAGE MODULUS Msi
COMPRESSION	$(90/\pm45/0)_{4S}$	1	294	70	4	532	77.2	.065	.0141	.095	41.8	6.06	.024		
		1	561	550	4	470	68.1	.205	.0116	.144	44.2	6.40	.046		
		2	294	70	4	512	74.2	.080	.0146	.068	38.7	5.62	.054		
		2	561	550	3	413	59.9	.027	.0110	-	41.5	6.02	.026		
		3	294	70	4	534	77.4	.074	.0147	.175	42.7	6.20	.118		
		3	561	550	8	448	65.0	.121	.0117	.120	43.5	6.30	.078		
COMPRESSION SANDWICH BEAM	$(0/\pm45/90)_S^*$	2	294	70	6	452	65.6	.093						61.9**	8.98
		2	561	550	5	407	59.1	.124						59.9**	8.68

* Celion 6000/PMR-15 ** Only 2 Specimens

Table 5.8-3: Summary of Rail Shear Tests - Celion 3000/PMR-15, Fiber Volume = 51.4%

TEST TYPE	LAYUP	COND. CODE	TEMPERATURE K	TEMPERATURE °F	NO. OF SPEC.	AVERAGE STRESS MPa	AVERAGE STRESS Ksi	AVERAGE STRESS [1]	STRAIN GAGE MODULUS GPa	STRAIN GAGE MODULUS Msi
RAIL SHEAR	$(\pm45)_{3S}$	1	294	70	3	324	47.0	.504	39.5	5.74
		1	561	550	3	330	47.8	.128	40.6	5.88
		2	294	70	2	358	52.0	.007	40.5	5.88
		2	561	550	2	240	34.8	.104	33.3	4.84

[1] Coefficient of Variation

Table 5.8-4: Summary of Flatwise Tension Tests - CELION 3000/PMR-15, Fiber Volume = 51.4%

TEST TYPE	LAYUP	COND. CODE	TEMPERATURE K	TEMPERATURE °F	NO. OF SPEC.	AVERAGE STRESS MPa	AVERAGE STRESS Ksi	▷1
FLATWISE TENSION LAM. TO LAM.	$(0/\pm45/90)_{2S}$	1	116	-250	3	20.76	3.011	.347
		1	294	70	3	26.43	3.833	.013
		1	561	550	3	8.84	1.282	.170
		2	116	-250	3	11.05	1.603	.548
		2	294	70	3	13.32	1.932	.186
		2	561	550	3	9.97	1.447	.392
FLATWISE TENSION LAM. TO CORE	$(0/\pm45/90)_{2S}$ TO HONEYCOMB CORE	1	116	-250	2	1.79	.259	.551
		1	294	70	3	6.23	.904	.130
		1	561	550	4	2.49	.361	.232
		2	116	-250	0	*	*	*
		2	294	70	3	5.05	.733	.023
		2	561	550	4	3.95	.573	.048

* Failure Due to Thermal Stresses

▷1 Coefficient of variation

6.0 CELION 6000/PMR-15 TESTING

This section presents the test matrix, specimen configurations, test procedures and test results for all testing of Celion 6000/PMR-15. There is also a data summary showing averages and coefficient of variations for each test type. The fiber volume of the Celion 6000/PMR-15 specimens was taken to be 65.3%. This was based on the average fiber volume obtained from failed tension specimens (3 specimens from each room temperature tension test for a total of 9 specimens). This fiber volume differs from the 58.5% obtained from the quality control tests (table 4.1-1), but was considered more accurate since it was obtained from actual test specimens.

The following test procedures were common to all tests: specimen temperatures were controlled using procedures described in section 6.2; all critical specimen dimensions were measured and recorded prior to test; load versus strain or deflection were recorded using a Baldwin recorder and the automatic data acquisition system, where applicable; specimen number, dimensions, test temperatures and ultimate failure load were recorded on test laboratory data sheets.

6.1 Test Matrix and Specimen Configuration

The design allowables test matrix for Celion 6000/PMR-15, Matrix 1A, is given in Table 6.1-1. Specimen configurations are shown in Figures 6.1-1 through 6.1-4. Specimens that were strain gaged are shown in Table 6.1-2. Strain gage locations are shown in Figures 6.1-5 through 6.1-7.

All the Celion 6000/PMR-15 specimens were conditioned to "baseline dry" prior to testing by exposure in a heated vacuum chamber to a temperature of 367K $\pm$ 6K (200^{0}F $\pm$ 10^{0}F) at a reduced pressure not greater than 500 Pa (3.8mm Hg) absolute. Vacuum was maintained using a diffusion pump. During drying, weights were tracked on two specimens of each test configuration. The specimens were weighed at frequent intervals and were considered dry

Table 6.1-1: Test Matrix IA - Design Allowables Celion 6000/PMR-15

TEST NO.	TEST METHOD	SPECIMEN* CONFIG.	LAMINATE LAY-UP	NO. OF TESTS AT TEMP. 116°K (-250°F)	294°K (70°F)	589°K (600°F)	TOTAL SPECIMENS
1	TENSION (ASTM D3039)	Figure 6.1-1	$[0]_8$	10	10	10	30
2			$[0/+45/90/-45]_S$	10	10	10	30
3			$[\pm 45]_{2S}$	10	10	10	30
4	COMPRESSION (IITRI)	Figure 6.1-2	$[0]_{16}$	10	10	10	30
5			$[0/+45/90/-45]_{2S}$	10	10	10	30
6			$[\pm 45]_{4S}$	10	10	10	30
7	IN-PLANE SHEAR ▷1	Figure 6.1-3	$[0/+45/90/-45]_S$	10	10	10	30
8	INTERLAMINAR SHEAR (ASTM D-2344)	Figure 6.1-4	$[0]_{20}$	5	5	5	15
						TOTAL	225

▷1 Per SESA Paper No. R79-105, May 1979

* All Specimens to be Conditioned "Base Line Dry"

when the measured weight loss differed from the previous weight loss by no more then 0.1 percent after three consecutive weight measurements made at one-week intervals. Specimens requiring strain gages had the gages installed prior to drying.

After a dry condition was established, the specimens were packaged in sealed bags and delivered to the test laboratories. At the test laboratories the specimens were stored in a vacuum oven maintained at $367^{o}K \pm 10^{o}K$ ($200^{o}F \pm 10^{o}F$) until they were removed just prior to testing.

Automatic Data Recording System

Data from specimens with extensometers or strain gages were processed using a Hewlett-Packard model 3052A automatic data acquisition system which consists of a model 3495A scanner, 3455A digital-voltmeter, (DVM),

9825A calculator, 9885M flexible disc drive and 7245 printer/plotter (see Fig. 6.1-8). Electrical signals from the load, strain and extensometer sensors are scanned in channel sequence, measured on the DVM and fed into the computer for computation in engineering units. The data is then stored in the flexible disc memory and can later be retrieved for additional computer functions to provide tabular listing on the printer of specimen number, modulus, Poisson's ratio, stress at failure and strain at failure.

A set of flexible disks with all the recorded data has been delivered to NASA, LaRC for their use in additional data reduction and analysis.

6.2 Test Temperatures

Test temperatures for the Celion 6000/PMR-15 tests were controlled as follows:

Room temperature tests were conducted in the normal laboratory environment (nominally 294^{O}K (70^{O}F)). No special environmental conditioning was used. For the elevated temperature tests, 589^{O}K (600^{O}F), specimens were placed in an enclosure (Figure 6.2-1) that was electrically heated using resistance heating elements. A radiation shield was placed between the heating coils and the specimen to prevent direct radiation impingement. Temperatures were controlled to $\pm$6K ($\pm$10^{O}F) by placing thermocouples on the specimens that were connected to a Thermac model 624A temperature controller.

For the 116^{O}K (-250^{O}F) tests, specimens were placed in an enclosure (see Figure 5.2-2) that was cooled by evaporating liquid nitrogen. Temperatures were controlled to $\pm$6K ($\pm$10^{O}F) by placing thermocouples on the specimens that were connected to an electro-pneumatic controller that pumped in the liquid/gaseous nitrogen.

All specimens were brought to the desired temperatures and then soaked for 10 minutes prior to test.

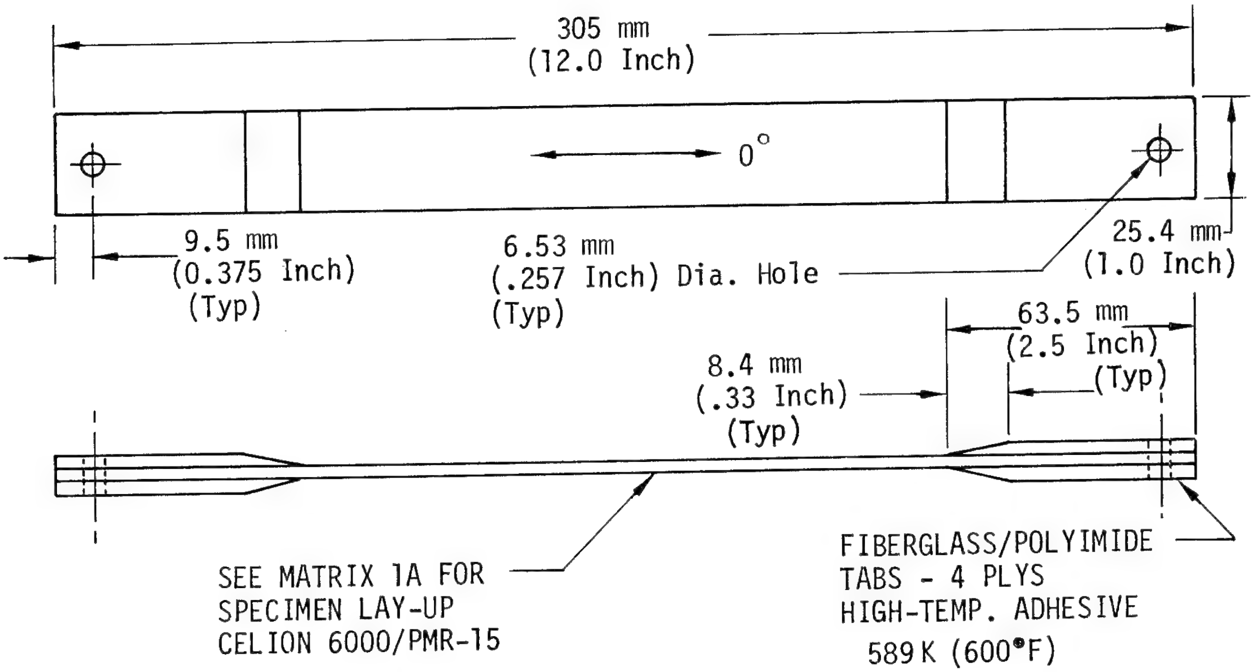


Figure 6.1-1: Celion 6000/PMR-15 Design Allowables Tension Specimen Configuration

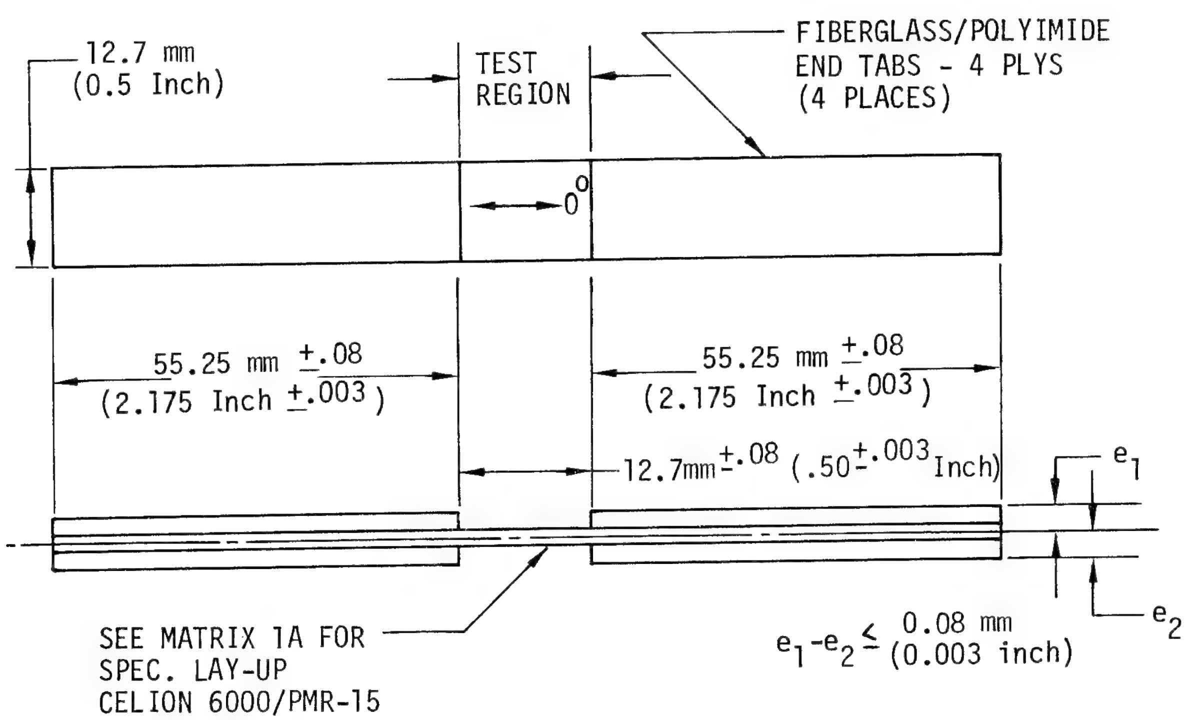


Figure 6.1-2: Celion 6000/PMR-15 Design Allowables IITRI Compression Specimen Configuration

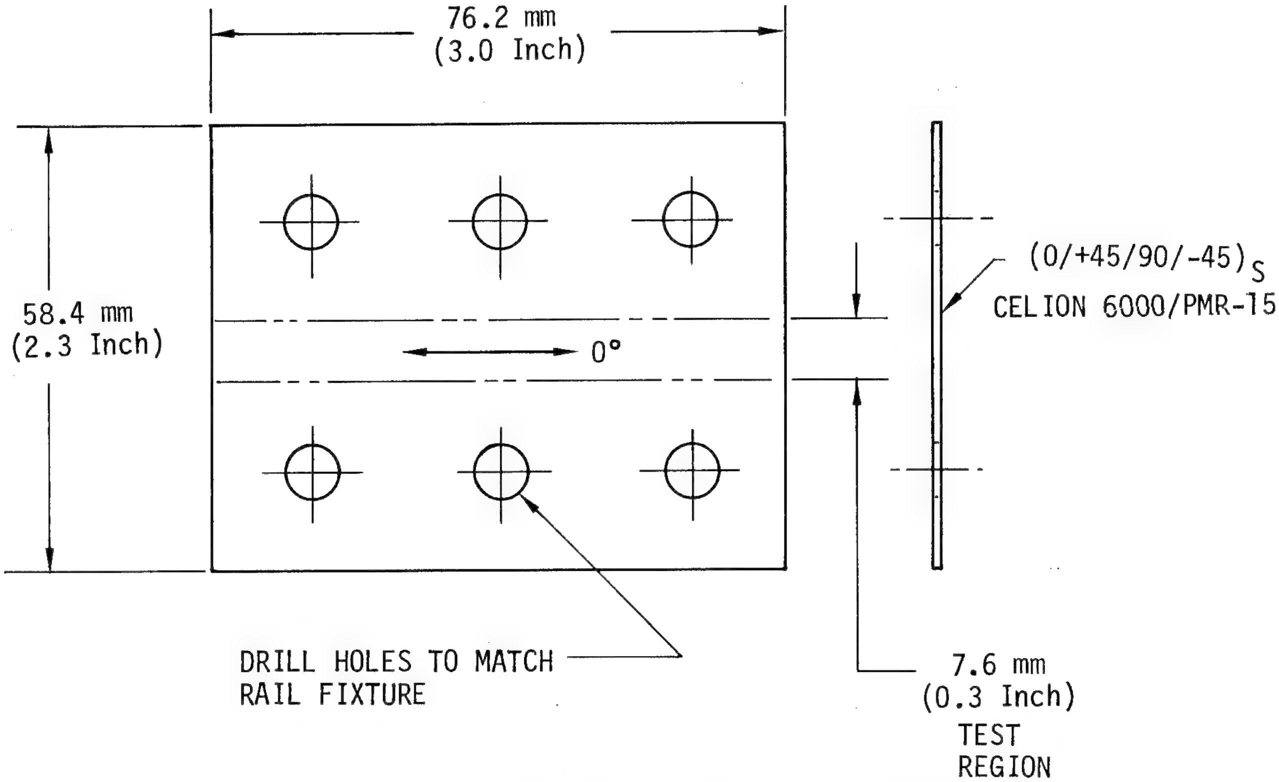


Figure 6.1-3: Celion 6000/PMR-15 Design Allowables
In-Plane Shear Specimen Configuration

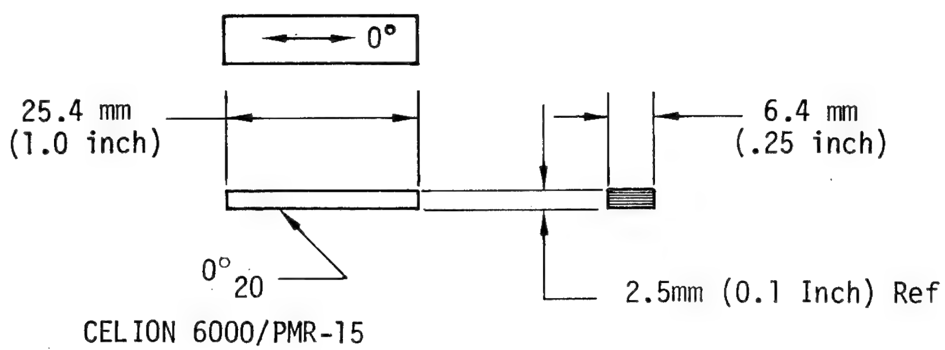


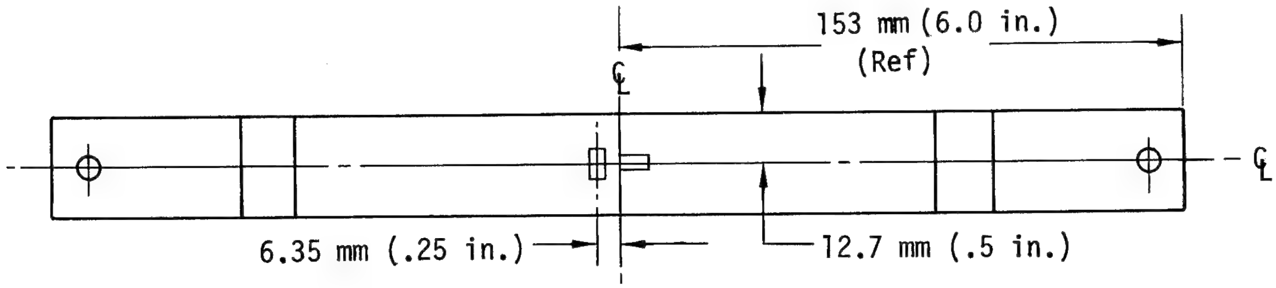
Figure 6.1-4: Celion 6000/PMR-15 Design Allowables
Interlaminar Shear Test Specimen

Table 6.1-2: Strain Gaged Specimens

TEST NUMBER	TEST METHOD	STRAIN GAGE LOCATION	NUMBER OF SPECIMENS STRAIN GAGED AT TEMPERATURE			TOTAL GAGED SPECIMENS
			-116 K (-250°F)	294 K (70°F)	589 K (600°F)	
1	TENSION (ASTM D3039)	Figure 6.1-5	3	3	3	9
2			3	3	3	9
3			3	3	3	9
4	COMPRESSION (IITRI)	Figure 6.1-6	3	3	3	9
5			3	3	3	9
6			3	3	3	9
7	INPLANE SHEAR [1]	Figure 6.1-7	3	3	3	9
8	INTERLAMINAR SHEAR (ASTM D-2344)	Not Applicable	0	0	0	0
						TOTAL 63

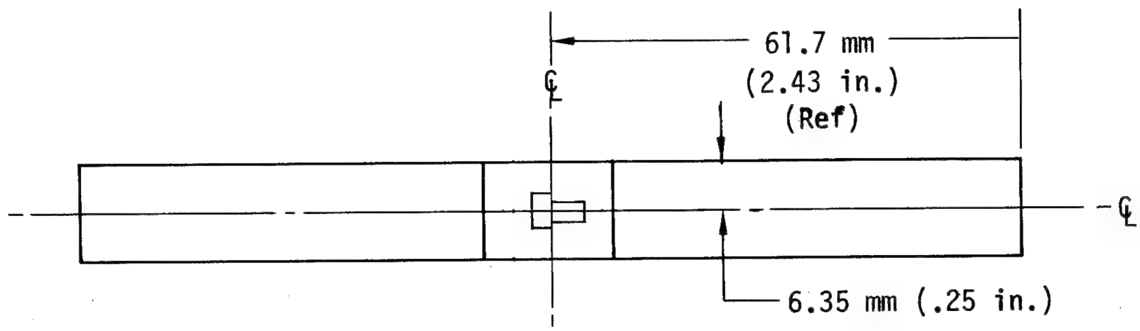
[1] Per SESA paper No. R79-105, May 1979

NOTE: Strain gaged specimens are included in total specimens in Matrix 1A, Table 3.



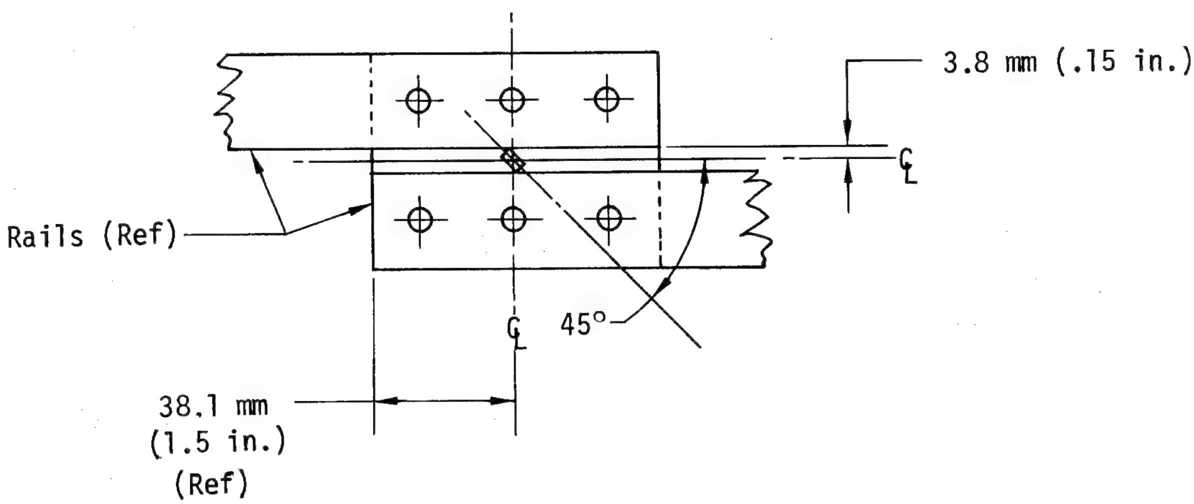
Two Sets of Gages Mounted Back-to-Back
(WK-00-250BG-350)

Figure 6.1-5: Celion 6000/PMR-15 Design Allowables Strain Gage Locations
Tension Specimen Tests 1 through 3



Two Sets of Gages Mounted Back-to-Back
(WK-00-125TM-350)

Figure 6.1-6: Celion 6000/PMR-15 Design Allowables Strain Gage Locations
Compression Specimen Tests 4 through 6



Two Sets of Gages Mounted Back to Back
(WK-00-06WR-350)

Figure 6.1-7: Celion 6000/PMR-15 Design Allowables Strain Gage Locations
In-Plane Shear Specimen Test 7

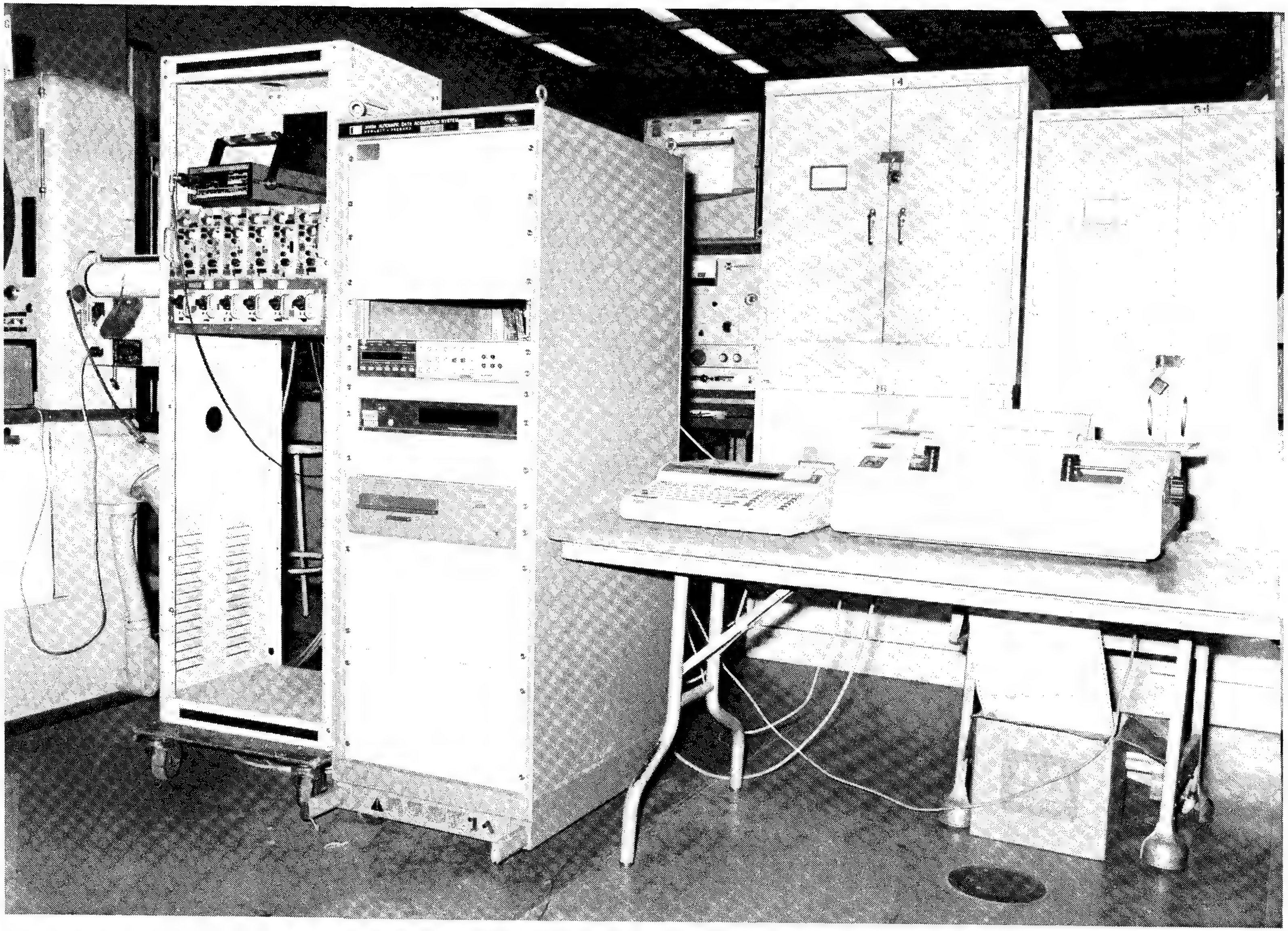


Figure 6.1-8: Automatic Data Recording System

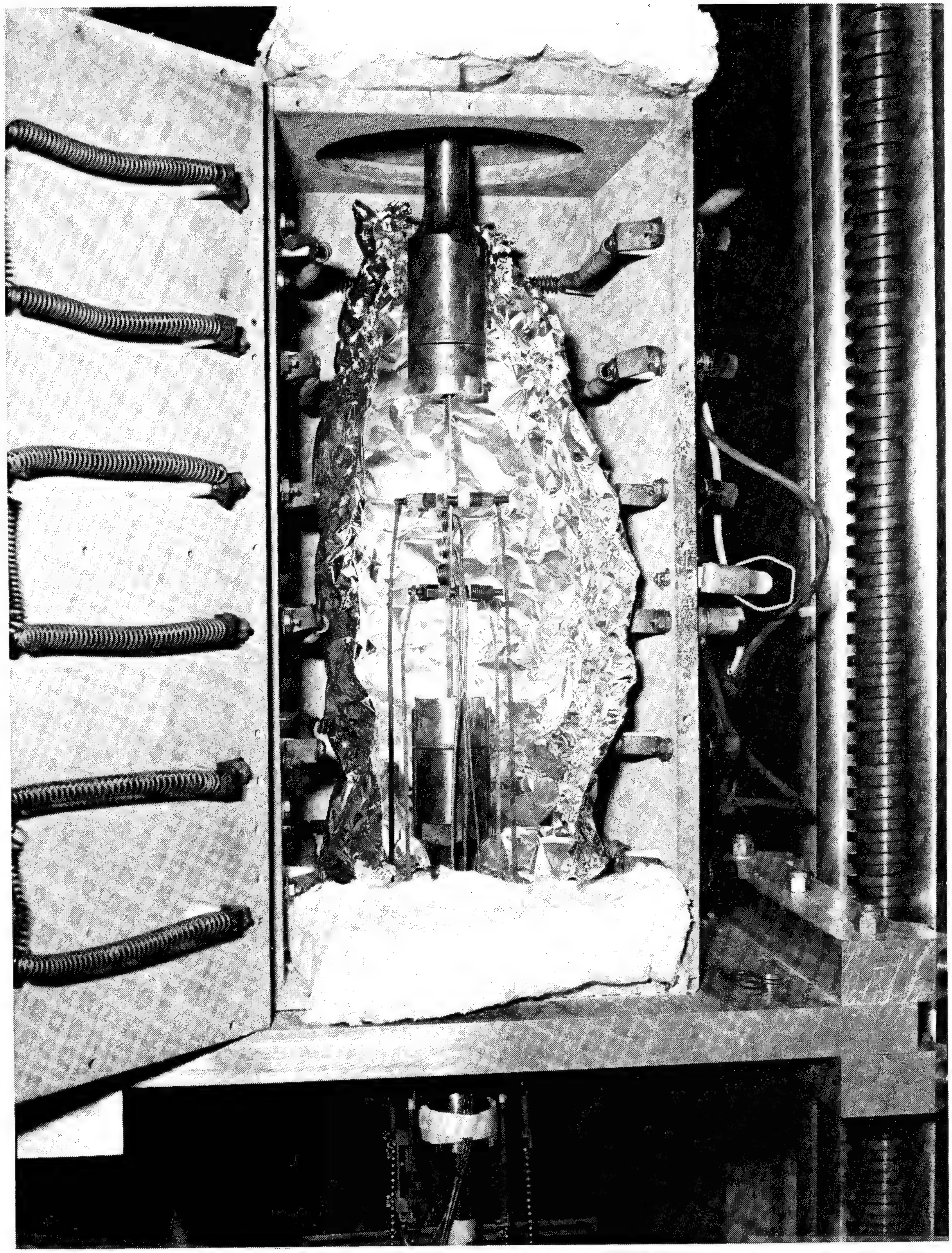


Figure 6.2-1: Elevated Temperature Enclosure
Celion 6000/PMR-15 Design Allowables

6.3 Tension Tests

This section presents test procedures and test results for tension tests of $(0)_8$, $(0/+45/90/-45)_S$ and $(\pm45)_{2S}$ laminates.

6.3.1 Test Procedures

Tension tests (tests 1, 2, and 3 of Matrix 1A) were conducted in accordance with ASTM D3039. Typical test set-ups are shown in Figures 6.3-1 and 6.3-2. Specimens were removed from the storage oven and installed in a Baldwin Universal test machine using Zapel grips. Extensometer clips were attached to the specimen using a 50.8 mm (2.0 inch) gage length and connected with ball chains to a TSM-D extensometer. Where applicable, strain gage output was recorded using the automatic data aquisition system. Thermocouples were installed at the center of the specimen and 50.8 mm (2.0 inch) above and below the center to monitor temperature gradients. For room temperature tests only, one thermocouple was used to assure that the specimen had cooled to room temperature after removal from the storage oven. A strain rate of 1.7×10^{-4} m/m-sec (.01 in/in-min) was applied and controlled using a strain pacer connected to the test machine.

6.3.2 Test Results

Test results are summarized in Tables 6.3-1 through 6.3-3. Typical failed specimens are shown in Figures 6.3-3 through 6.3-5.

Test results are plotted as functions of temperature in Figure 6.3-6 through 6.3-11. The data show that tension strength and modulus were not significantly affected by temperature for the $(0)_8$ and $(0/+45/90/-45)_S$ layups. Tension strength and modulus of the $(\pm45)_{2S}$ laminates decreased with increasing temperature as expected since this is a matrix dominated layup. Failure strains for the three layups were approximately 1.2% with

the exception of the elevated temperature $(\pm 45)_{2S}$ layup which had a failure strain of 8.0%.

Tangent modulus and Poisson's ratio were obtained at a strain level of 0.2%. At this strain level, incremental changes in back-to-back longitudinal strain gage output of all tension specimens varied from 0% to 15% with an average of 4%.

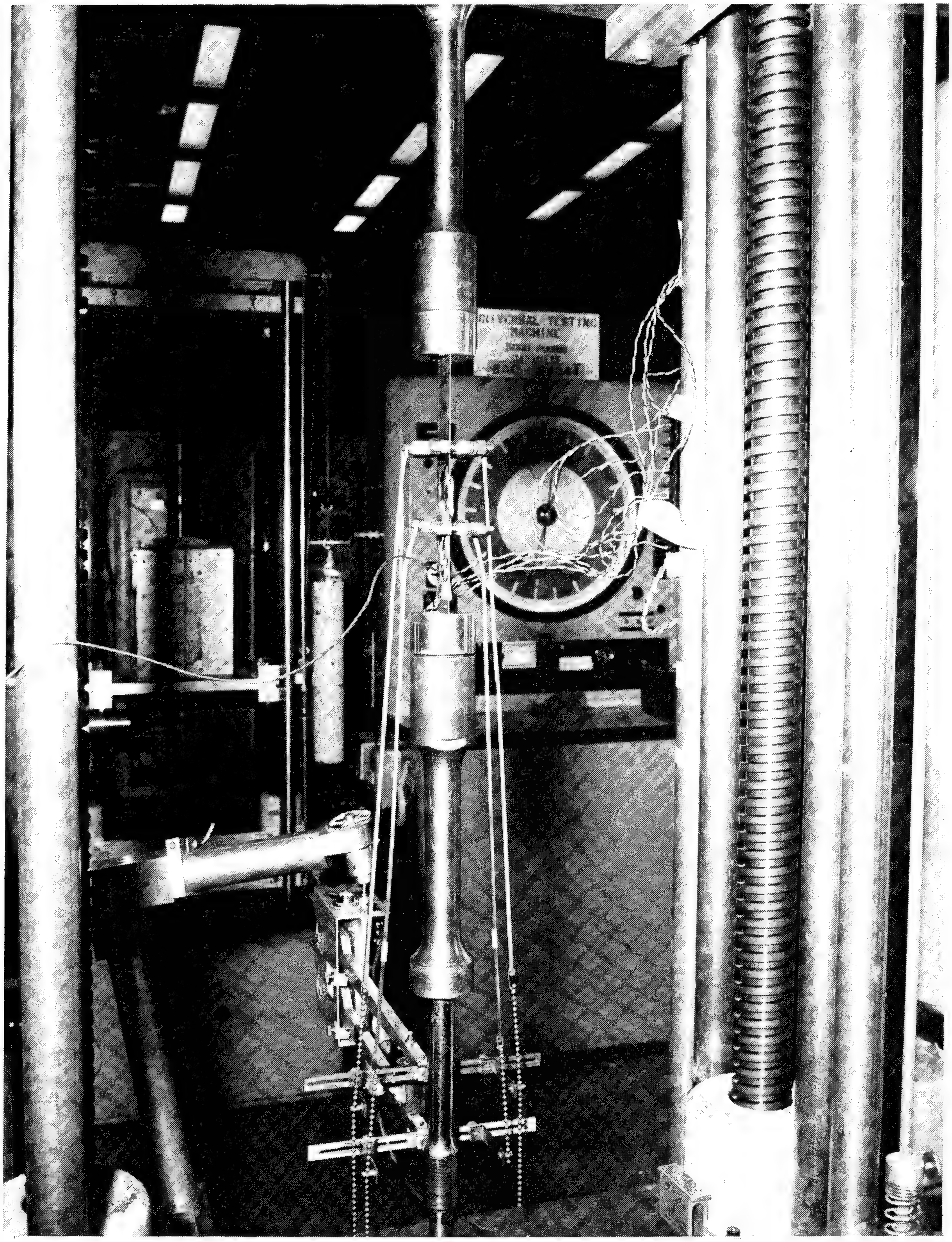


Figure 6.3-1: Tension Test Setup
Celion 6000/PMR-15 Design Allowables 294K (70°F)

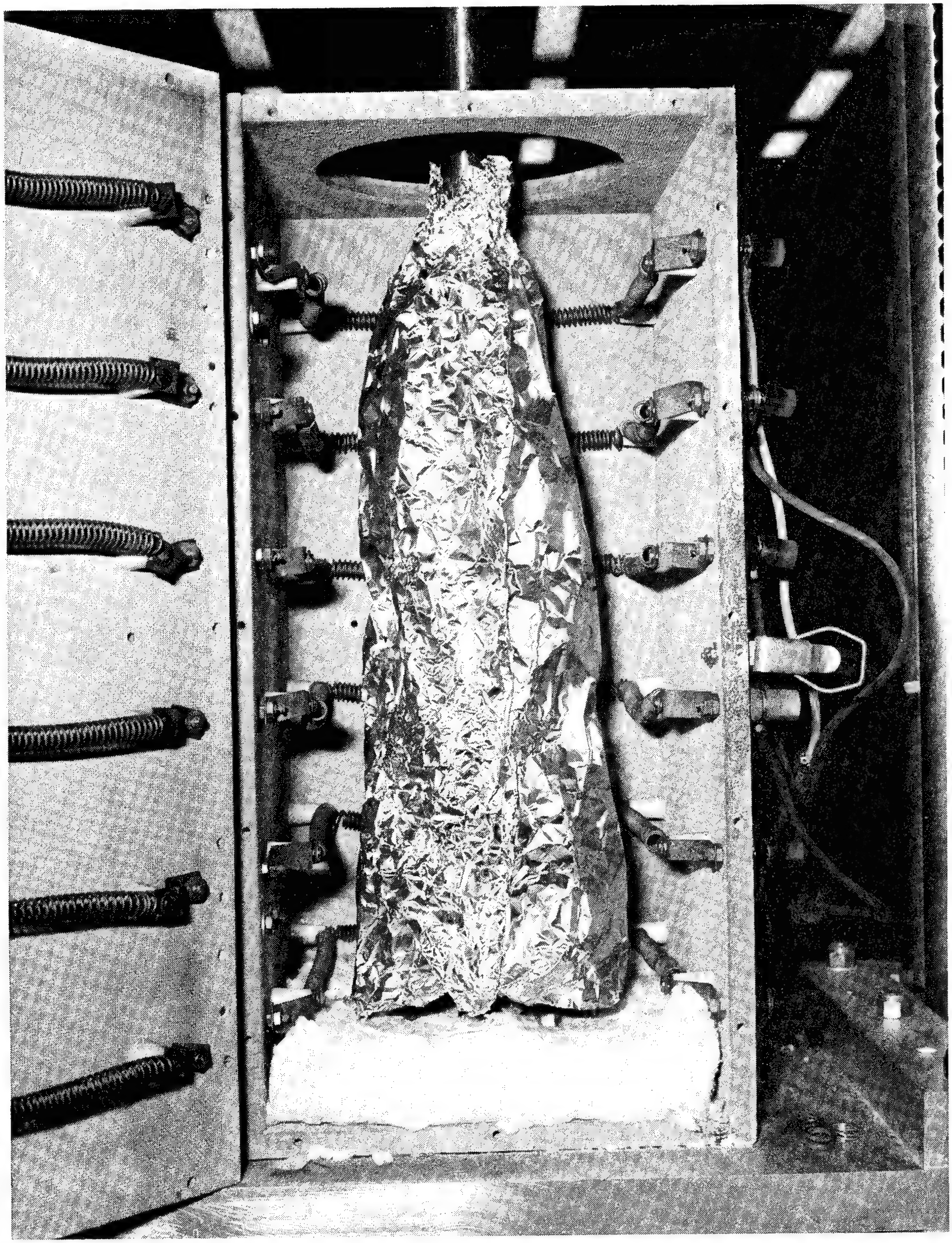


Figure 6.3-2: Tension Test Setup
Celion 6000/PMR-15 Design Allowables 589K (600°F)

TABLE 6.3-1. CELION 6000/PMR-15 DESIGN ALLOWABLES TENSION TESTS [0]8 LAYUP

(a) SI UNITS

						EXTENSOMETER DATA		STRAIN GAGE DATA ε = .002	
SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	FAILURE STRAIN	TENSION MODULUS GPA	TENSION MODULUS GPA	POISSON'S RATIO
1A-1-1	1.11	25.116	116.	42881.	1538.	.0114	132.		
1A-1-2	1.12	25.370	116.	48263.	1703.	.0128	130.		
1A-1-3	1.12	25.298	116.	42303.	1489.	.0112	129.		
1A-1-4	1.10	25.451	116.	42392.	1503.	.0114	125.		
1A-1-5	1.10	25.392	116.	44460.	1579.	.0118	142.		
1A-1-6	1.13	25.342	116.	46439.	1620.	.0108	143.		
1A-1-7	1.12	25.453	116.	44794.	1565.	.0112	134.		
1A-1-8	1.07	25.474	116.	47329.	1744.	.0092	148.	137.	.378
1A-1-9	1.15	25.382	116.	46907.	1606.	.0116	134.	132.	.387**
1A-1-10	1.13	25.464	116.	44527.	1544.	NO DATA	133.	134.	.385
1A-1-11*	1.09	25.486	294.	44771.	1613.	.0114	136.		
1A-1-12	1.14	25.438	294.	43535.	1503.	.0112	140.		
1A-1-13	1.15	25.423	294.	41880.	1434.	.0112	124.		
1A-1-14	1.11	25.245	294.	38989.	1386.	.0102	133.		
1A-1-15	1.14	25.375	294.	40790.	1413.	.0108	128.		
1A-1-16	1.10	25.189	294.	43570.	1565.	.0115	133.		
1A-1-17	1.13	25.443	294.	43726.	1510.	.0118	125.		
1A-1-18	1.10	25.215	294.	34429.	1241.	.0094	131.	134.	.343
1A-1-19	1.11	25.270	294.	49398.	1751.	.0122	134.	137.	.329
1A-1-20	1.10	25.476	294.	47173.	1675.	.0120	135.	136.	.327
1A-1-21	1.15	25.527	589.	47329.	1606.	.0120	141.		
1A-1-22	1.12	25.466	589.	45372.	1586.	.0128	121.		
1A-1-23	1.12	25.469	589.	45283.	1579.	.0110	145.		
1A-1-24	1.17	25.413	589.	46751.	1572.	.0122	141.		
1A-1-25	1.11	25.438	589.	44304.	1565.	.0118	137.		
1A-1-26	1.16	25.484	589.	45683.	1544.	.0112	134.		
1A-1-27	1.09	25.535	589.	47129.	1689.	.0136	123.		
1A-1-28	1.08	25.357	589.	46195.	1682.	.0134	137.	145.	.305
1A-1-29	1.12	25.458	589.	45038.	1579.	NO DATA	146.	141.	.291
1A-1-30	1.12	25.382	589.	45906.	1620.	.0134	123.	143.	.353

UNLESS NOTED STRAIN RATE = 1.7 E-04 1/SEC
* STRAIN RATE = 3.3 E-04 1/SEC
** 1 TRANVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.3-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA TENSION MODULUS MSI	STRAIN GAGE DATA $\varepsilon = .002$ TENSION MODULUS MSI	STRAIN GAGE DATA $\varepsilon = .002$ POISSON'S RATIO
1A-1-1	.0437	0.9888	-250.	9640.	223.	.0114	19.2		
1A-1-2	.0439	0.9988	-250.	10850.	247.	.0128	18.9		
1A-1-3	.0441	0.9960	-250.	9510.	216.	.0112	18.7		
1A-1-4	.0435	1.0020	-250.	9530.	218.	.0114	18.1		
1A-1-5	.0435	0.9997	-250.	9995.	229.	.0118	20.6		
1A-1-6	.0444	0.9977	-250.	10440.	235.	.0108	20.7		
1A-1-7	.0441	1.0021	-250.	10070.	227.	.0112	19.4		
1A-1-8	.0420	1.0029	-250.	10640.	253.	.0092	21.5	19.9	.378
1A-1-9	.0452	0.9993	-250.	10545.	233.	.0116	19.5	19.2	.387**
1A-1-10	.0446	1.0025	-250.	10010.	224.	NO DATA	19.3	19.5	.385
1A-1-11*	.0428	1.0034	70.	10065.	234.	.0114	19.7		
1A-1-12	.0447	1.0015	70.	9787.	218.	.0112	20.3		
1A-1-13	.0452	1.0009	70.	9415.	208.	.0112	18.0		
1A-1-14	.0438	0.9939	70.	8765.	201.	.0102	19.3		
1A-1-15	.0447	0.9990	70.	9170.	205.	.0108	18.5		
1A-1-16	.0435	0.9917	70.	9795.	227.	.0115	19.3		
1A-1-17	.0446	1.0017	70.	9830.	219.	.0118	18.2		
1A-1-18	.0432	0.9927	70.	7740.	180.	.0094	19.0	19.5	.343
1A-1-19	.0438	0.9949	70.	11105.	254.	.0122	19.4	19.8	.329
1A-1-20	.0435	1.0030	70.	10605.	243.	.0120	19.6	19.7	.327
1A-1-21	.0453	1.0050	600.	10640.	233.	.0120	20.5		
1A-1-22	.0442	1.0026	600.	10200.	230.	.0128	17.5		
1A-1-23	.0442	1.0027	600.	10180.	229.	.0110	21.0		
1A-1-24	.0459	1.0005	600.	10510.	228.	.0122	20.5		
1A-1-25	.0437	1.0015	600.	9960.	227.	.0118	19.8		
1A-1-26	.0455	1.0033	600.	10270.	224.	.0112	19.5		
1A-1-27	.0430	1.0053	600.	10595.	245.	.0136	17.8		
1A-1-28	.0425	0.9983	600.	10385.	244.	.0134	19.9	21.1	.305
1A-1-29	.0441	1.0023	600.	10125.	229.	NO DATA	21.2	20.5	.291
1A-1-30	.0439	0.9993	600.	10320.	235.	.0134	17.8	20.8	.353

UNLESS NOTED STRAIN RATE $\doteq$ .01 1/MIN
* STRAIN RATE = .02 1/MIN
** 1 TRANVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.3-2. CELION 6000/PMR-15 DESIGN ALLOWABLES TENSION TESTS [0/+45/90/-45]S LAYUP

(a) SI UNITS

						EXTENSOMETER DATA		STRAIN GAGE DATA ε = .002	
SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	FAILURE STRAIN	TENSION MODULUS GPA	TENSION MODULUS GPA	POISSON'S RATIO
1A-2-1	1.10	25.451	116.	15569.	556.	.0134	45.		
1A-2-2	1.12	25.316	116.	15391.	544.	.0124	46.		
1A-2-3	1.16	25.563	116.	15391.	520.	.0124	43.		
1A-2-4	1.15	25.489	116.	15569.	531.	.0120	43.		
1A-2-5	1.11	25.339	116.	14590.	518.	.0116	45.		
1A-2-6	1.13	25.446	116.	16280.	565.	.0122	46.		
1A-2-7	1.12	25.448	116.	15124.	532.	.0118	42.		
1A-2-8	1.09	25.433	116.	14657.	527.	.0126	44.	50.3	.330
1A-2-9	1.05	25.382	116.	14323.	538.	.0106	49.	50.3	.294
1A-2-10	1.10	25.408	116.	12811.	455.	.0098	46.	51.4	.326**
1A-2-11	1.10	25.532	294.	14657.	520.	.0118	48.		
1A-2-12	1.12	25.430	294.	16058.	563.	.0122	48.		
1A-2-13	1.13	25.565	294.	15969.	555.	.0108	48.		
1A-2-14	1.09	25.591	294.	16103.	576.	.0130	50.		
1A-2-15	1.15	25.560	294.	16369.	559.	.0130	48.		
1A-2-16	1.13	25.552	294.	16347.	565.	.0130	51.		
1A-2-17	1.13	25.484	294.	14123.	492.	.0126	43.		
1A-2-18	1.13	25.476	294.	15547.	540.	.0116	49.	51.0	.336
1A-2-19	1.14	25.260	294.	10631.	371.	.0082	51.	49.2	.330
1A-2-20	1.10	25.430	294.	14101.	504.	.0114	48.	50.5	.353
1A-2-21	1.10	25.428	589.	14924.	534.	.0118	46.		
1A-2-22	1.13	25.565	589.	15413.	532.	.0123	47.		
1A-2-23	1.16	25.469	589.	14857.	503.	.0109	48.		
1A-2-24	1.13	25.509	589.	15480.	537.	.0125	45.		
1A-2-25	1.11	25.552	589.	13656.	481.	.0112	46.		
1A-2-26	1.14	25.583	589.	15636.	537.	.0129	45.		
1A-2-27	1.12	25.545	589.	15391.	536.	.0118	47.		
1A-2-28	1.12	25.476	589.	14857.	519.	.0124	46.	51.0*	.354
1A-2-29	1.12	25.489	589.	14101.	495.	.0115	46.	49.4	.346
1A-2-30	1.13	25.540	589.	13923.	481.	.0114	45.	48.7	.348

UNLESS NOTED STRAIN RATE = 1.7 E-4 1/SEC
* 1 LONGITUDINAL STRAIN GAGE FAULTY
** 1 TRANVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.3-2. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	EXTENSOMETER DATA FAILURE STRAIN	EXTENSOMETER DATA TENSION MODULUS MSI	STRAIN GAGE DATA ϵ = .002 TENSION MODULUS MSI	STRAIN GAGE DATA ϵ = .002 POISSON'S RATIO
1A-2-1	.0433	1.0020	-250.	3500.	80.7	.0134	6.5		
1A-2-2	.0440	0.9967	-250.	3460.	78.9	.0124	6.6		
1A-2-3	.0456	1.0064	-250.	3460.	75.4	.0124	6.2		
1A-2-4	.0453	1.0035	-250.	3500.	77.0	.0120	6.3		
1A-2-5	.0437	0.9976	-250.	3280.	75.2	.0116	6.5		
1A-2-6	.0446	1.0018	-250.	3660.	81.9	.0122	6.6		
1A-2-7	.0440	1.0019	-250.	3400.	77.1	.0118	6.1		
1A-2-8	.0431	1.0013	-250.	3295.	76.4	.0126	6.4	7.30	.330
1A-2-9	.0413	0.9993	-250.	3220.	78.0	.0106	7.1	7.30	.294
1A-2-10	.0432	1.0003	-250.	2880.	66.0	.0098	6.7	7.46	.326**
1A-2-11	.0435	1.0052	70.	3295.	75.4	.0118	7.0		
1A-2-12	.0442	1.0012	70.	3610.	81.6	.0122	7.0		
1A-2-13	.0443	1.0065	70.	3590.	80.5	.0108	7.0		
1A-2-14	.0430	1.0075	70.	3620.	83.6	.0130	7.2		
1A-2-15	.0451	1.0063	70.	3680.	81.1	.0130	7.0		
1A-2-16	.0446	1.0060	70.	3675.	81.9	.0130	7.4		
1A-2-17	.0444	1.0033	70.	3175.	71.3	.0126	6.2		
1A-2-18	.0445	1.0030	70.	3495.	78.3	.0116	7.1	7.39	.336
1A-2-19	.0447	0.9945	70.	2390.	53.8	.0082	7.4	7.14	.330
1A-2-20	.0433	1.0012	70.	3170.	73.1	.0114	7.0	7.33	.353
1A-2-21	.0433	1.0011	600.	3355.	77.4	.0118	6.6		
1A-2-22	.0446	1.0065	600.	3465.	77.2	.0123	6.8		
1A-2-23	.0456	1.0027	600.	3340.	73.0	.0109	6.9		
1A-2-24	.0445	1.0043	600.	3480.	77.9	.0125	6.5		
1A-2-25	.0437	1.0060	600.	3070.	69.8	.0112	6.6		
1A-2-26	.0448	1.0072	600.	3515.	77.9	.0129	6.5		
1A-2-27	.0442	1.0057	600.	3460.	77.8	.0118	6.8		
1A-2-28	.0442	1.0030	600.	3340.	75.3	.0124	6.7	7.39*	.354
1A-2-29	.0440	1.0035	600.	3170.	71.8	.0115	6.7	7.17	.346
1A-2-30	.0446	1.0055	600.	3130.	69.8	.0114	6.5	7.06	.348

UNLESS NOTED STRAIN RATE = .01 1/MIN
* 1 LONGITUDINAL STRAIN GAGE FAULTY
** 1 TRANVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.3-3. CELION 6000/PMR-15 DESIGN ALLOWABLES TENSION TESTS (+-45)2S LAYUP

(a) SI UNITS

SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	EXTENSOMETER DATA: FAILURE STRAIN	EXTENSOMETER DATA: TENSION MODULUS GPA	STRAIN GAGE DATA ε = .002: TENSION MODULUS GPA	STRAIN GAGE DATA ε = .002: POISSON'S RATIO
1A-3-1	1.15	25.471	116.	3648.	125.	.0110	19.		
1A-3-2	1.08	25.489	116.	3621.	131.	.0160	19.		
1A-3-3	1.10	25.451	116.	3621.	130.	.0158	19.		
1A-3-4	1.11	25.400	116.	3630.	129.	.0102	21.		
1A-3-5	1.09	25.453	116.	3594.	130.	.0146	21.		
1A-3-6	1.09	25.474	116.	3594.	130.	.0118	17.		
1A-3-7	1.10	25.517	116.	3692.	132.	.0136	21.		
1A-3-8	1.08	25.400	116.	3603.	132.	NO DATA	22.	21.0	.778
1A-3-9	1.07	24.994	116.	3648.	136.	.0112	21.	22.0	.752
1A-3-10	1.07	25.019	116.	3594.	134.	.0108	20.	19.2	.687
1A-3-11	1.10	25.535	294.	3470.	123.	.0160	17.		
1A-3-12	1.10	25.395	294.	3425.	122.	.0108	17.		
1A-3-13	1.07	25.207	294.	3301.	122.	.0140	20.		
1A-3-14	1.11	25.527	294.	3461.	122.	.0120	17.		
1A-3-15	1.11	25.349	294.	3416.	121.	.0144	17.		
1A-3-16	1.10	25.278	294.	3416.	123.	.0132	17.		
1A-3-17	1.10	25.174	294.	3443.	124.	.0126	18.		
1A-3-18	1.08	25.420	294.	3505.	128.	.0124	19.	17.6	.850
1A-3-19	1.08	25.235	294.	3474.	127.	.0118	19.	16.8	.903
1A-3-20	1.09	25.362	294.	3452.	125.	.0118	17.	17.9	.867
1A-3-21	1.10	25.344	589.	2918.	104.	.0788	14.		
1A-3-22*	1.09	25.456	589.	2785.	101.	.0672	10.		
1A-3-23*	1.13	25.476	589.	3132.	109.	.0912	11.		
1A-3-24*	1.09	25.497	589.	3203.	114.	.0984	13.		
1A-3-25**	1.11	25.476	589.	3136.	111.	.0792	11.		
1A-3-26**	1.09	25.425	589.	2971.	108.	.0744	11.		
1A-3-27**	1.10	25.400	589.	3100.	111.	.0840	12.		
1A-3-28**	1.09	25.494	589.	3078.	110.	.0840	12.	8.8	.842
1A-3-29**	1.09	25.273	589.	3229.	117.	.0872	12.	8.5	.835
1A-3-30**	1.10	25.443	589.	3109.	110.	.0808	11.	8.0	.801
1A-3-31**	1.11	25.255	589.	2527.	90.	.0496	13.		

UNLESS NOTED STRAIN RATE = 1.7 E-04 1/SEC
* STRAIN RATE = 6.7 E-04 1/SEC
** STRAIN RATE = 1.3 E-03 1/SEC

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.3-3. CONCLUDED

(b) U.S. CUSTUMARY UNITS

						EXTENSOMETER DATA		STRAIN GAGE DATA ε = .002	
SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	FAILURE STRAIN	TENSION MODULUS MSI	TENSION MODULUS MSI	POISSON'S RATIO
1A-3-1	.0453	1.0028	-250.	820.	18.1	.0110	2.7		
1A-3-2	.0427	1.0035	-250.	814.	19.0	.0160	2.8		
1A-3-3	.0433	1.0020	-250.	814.	18.8	.0158	2.8		
1A-3-4	.0437	1.0000	-250.	816.	18.7	.0102	3.1		
1A-3-5	.0428	1.0021	-250.	808.	18.8	.0146	3.1		
1A-3-6	.0428	1.0029	-250.	808.	18.8	.0118	2.5		
1A-3-7	.0433	1.0046	-250.	830.	19.1	.0136	3.0		
1A-3-8	.0425	1.0000	-250.	810.	19.1	NO DATA	3.2	3.04	.778
1A-3-9	.0423	0.9840	-250.	820.	19.7	.0112	3.0	3.19	.752
1A-3-10	.0423	0.9850	-250.	808.	19.4	.0108	2.9	2.78	.687
1A-3-11	.0432	1.0053	70.	780.	17.9	.0160	2.4		
1A-3-12	.0433	0.9998	70.	770.	17.7	.0108	2.5		
1A-3-13	.0421	0.9924	70.	742.	17.7	.0140	2.9		
1A-3-14	.0437	1.0050	70.	778.	17.7	.0120	2.5		
1A-3-15	.0436	0.9980	70.	768.	17.6	.0144	2.5		
1A-3-16	.0432	0.9952	70.	768.	17.8	.0132	2.4		
1A-3-17	.0434	0.9911	70.	774.	18.0	.0126	2.6		
1A-3-18	.0425	1.0008	70.	788.	18.5	.0124	2.8	2.55	.850
1A-3-19	.0427	0.9935	70.	781.	18.4	.0118	2.7	2.43	.903
1A-3-20	.0429	0.9985	70.	776.	18.1	.0118	2.5	2.59	.867
1A-3-21	.0434	0.9978	600.	656.	15.1	.0788	2.0		
1A-3-22*	.0428	1.0022	600.	626.	14.6	.0672	1.5		
1A-3-23*	.0443	1.0030	600.	704.	15.8	.0912	1.6		
1A-3-24*	.0431	1.0038	600.	720.	16.6	.0984	1.9		
1A-3-25**	.0437	1.0030	600.	705.	16.1	.0792	1.6		
1A-3-26**	.0428	1.0010	600.	668.	15.6	.0744	1.6		
1A-3-27**	.0432	1.0000	600.	697.	16.1	.0840	1.7		
1A-3-28**	.0430	1.0037	600.	692.	16.0	.0840	1.7	1.28	.842
1A-3-29**	.0431	0.9950	600.	726.	16.9	.0872	1.8	1.23	.835
1A-3-30**	.0435	1.0017	600.	699.	16.0	.0808	1.6	1.16	.801
1A-3-31**	.0438	0.9943	600.	568.	13.0	.0496	1.9		

UNLESS NOTED STRAIN RATE = .01 1/MIN
* STRAIN RATE = .04 1/MIN
** STRAIN RATE = .08 1/MIN

NOTE: FIBER VOLUME = 65.3 %

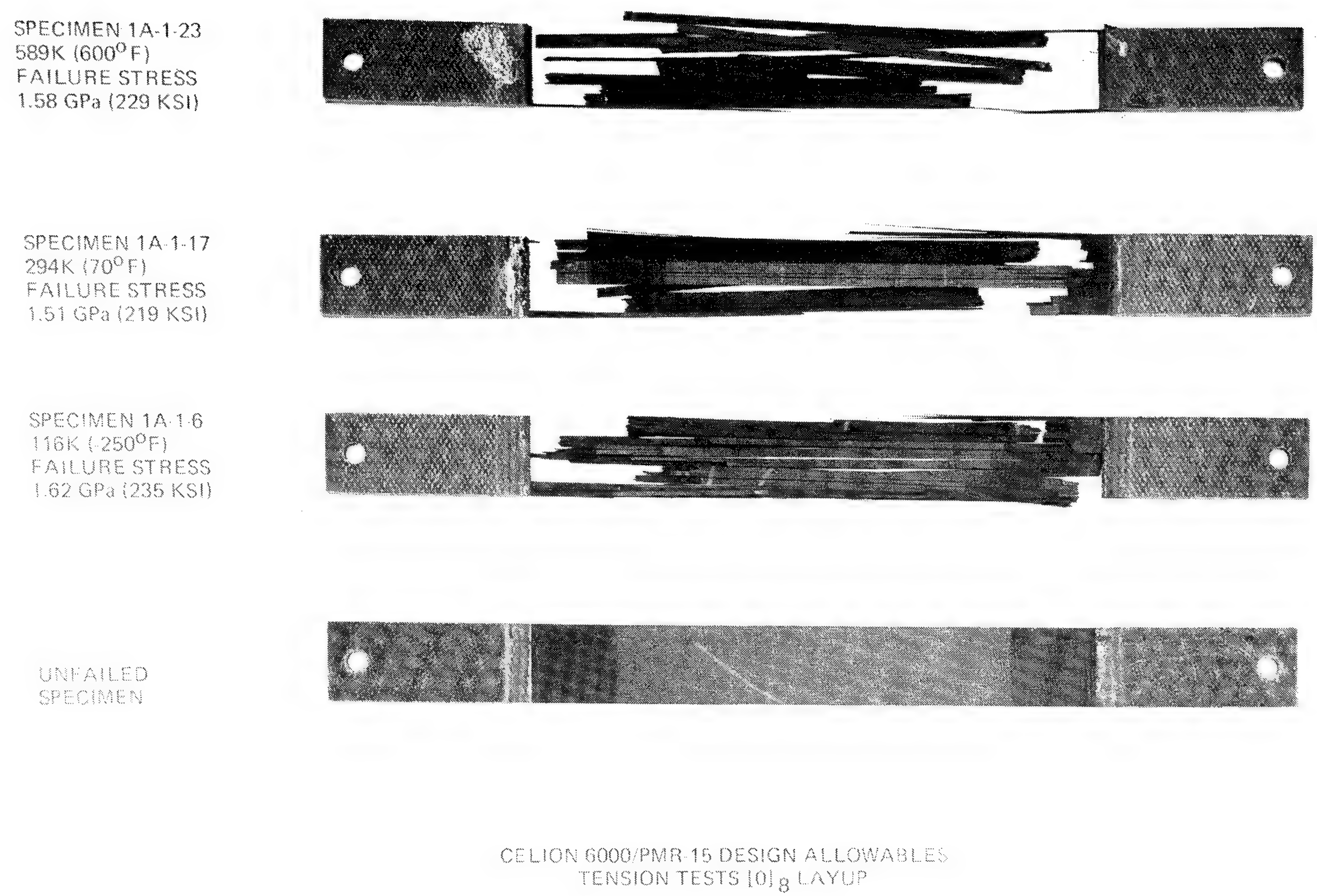


Figure 6.3-3: Celion 6000/PMR-15 Design Allowables $[0]_8$ Layup - Failed Specimens

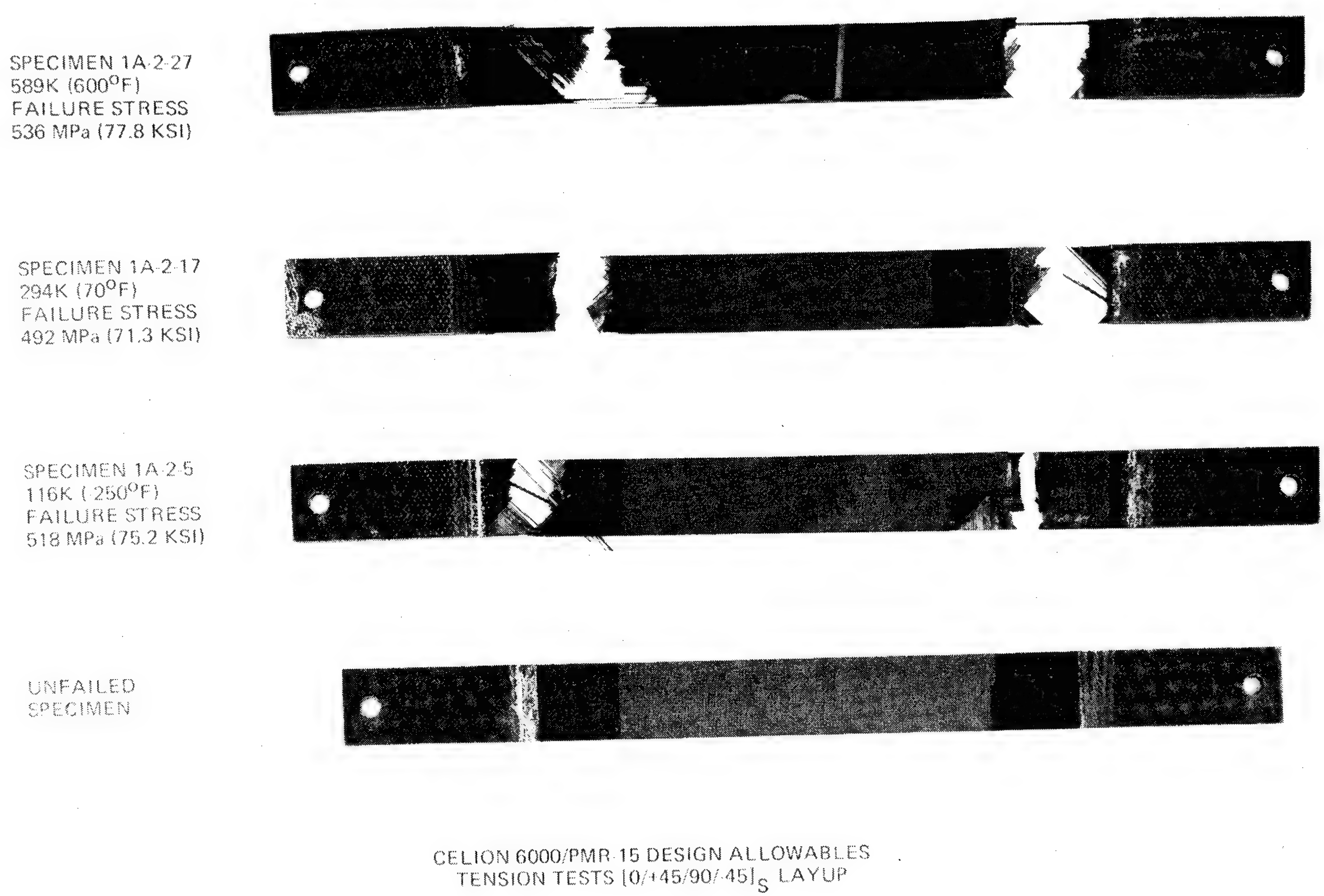


Figure 6.3-4: Celion 6000/PMR-15 Design Allowables $[0/+45/90/-45]_S$ Layup - Failed Specimens

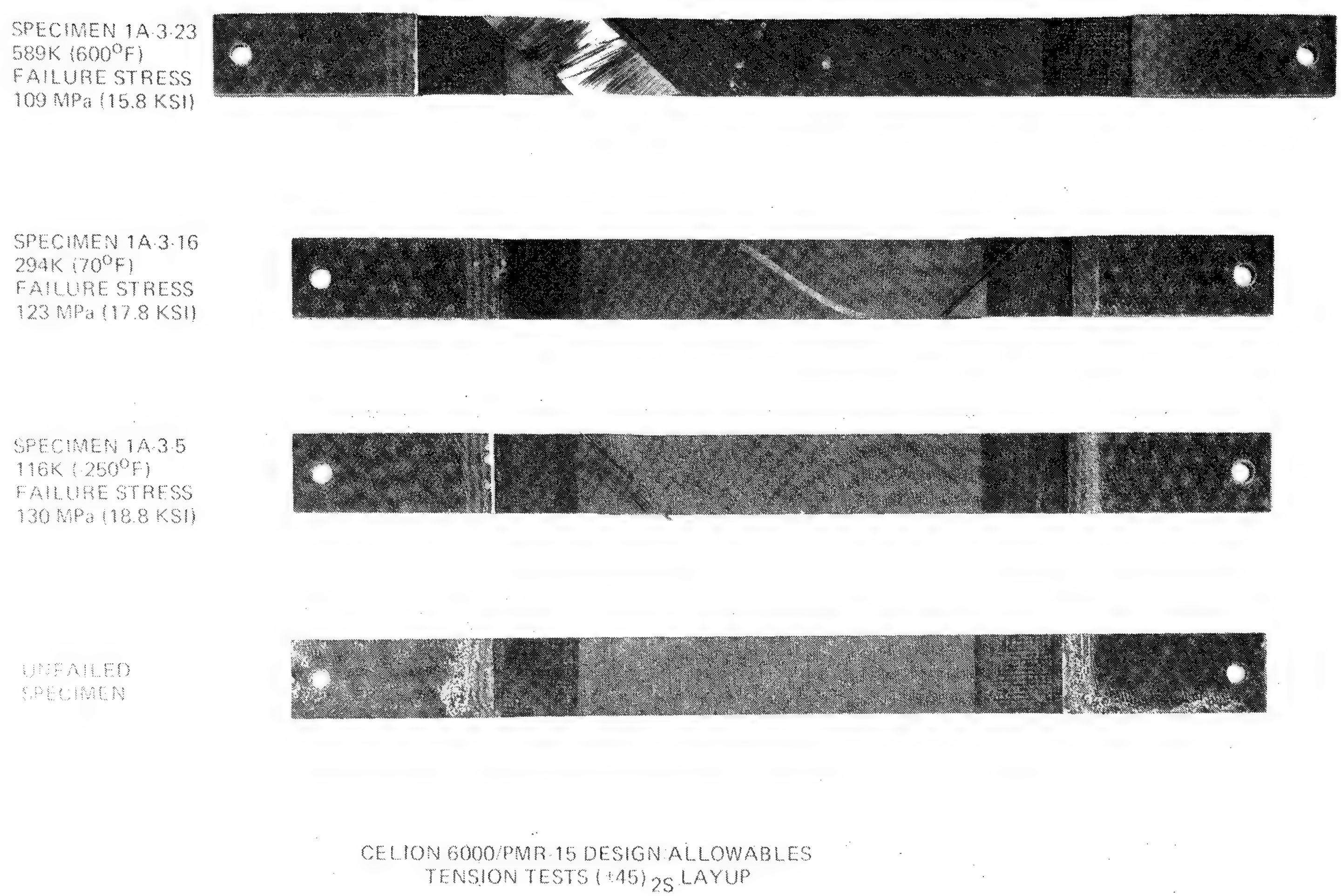


Figure 6.3-5: Celion 6000/PMR-15 Design Allowables Tension Tests $[\pm 45]_{2S}$ Layup - Failed Specimens

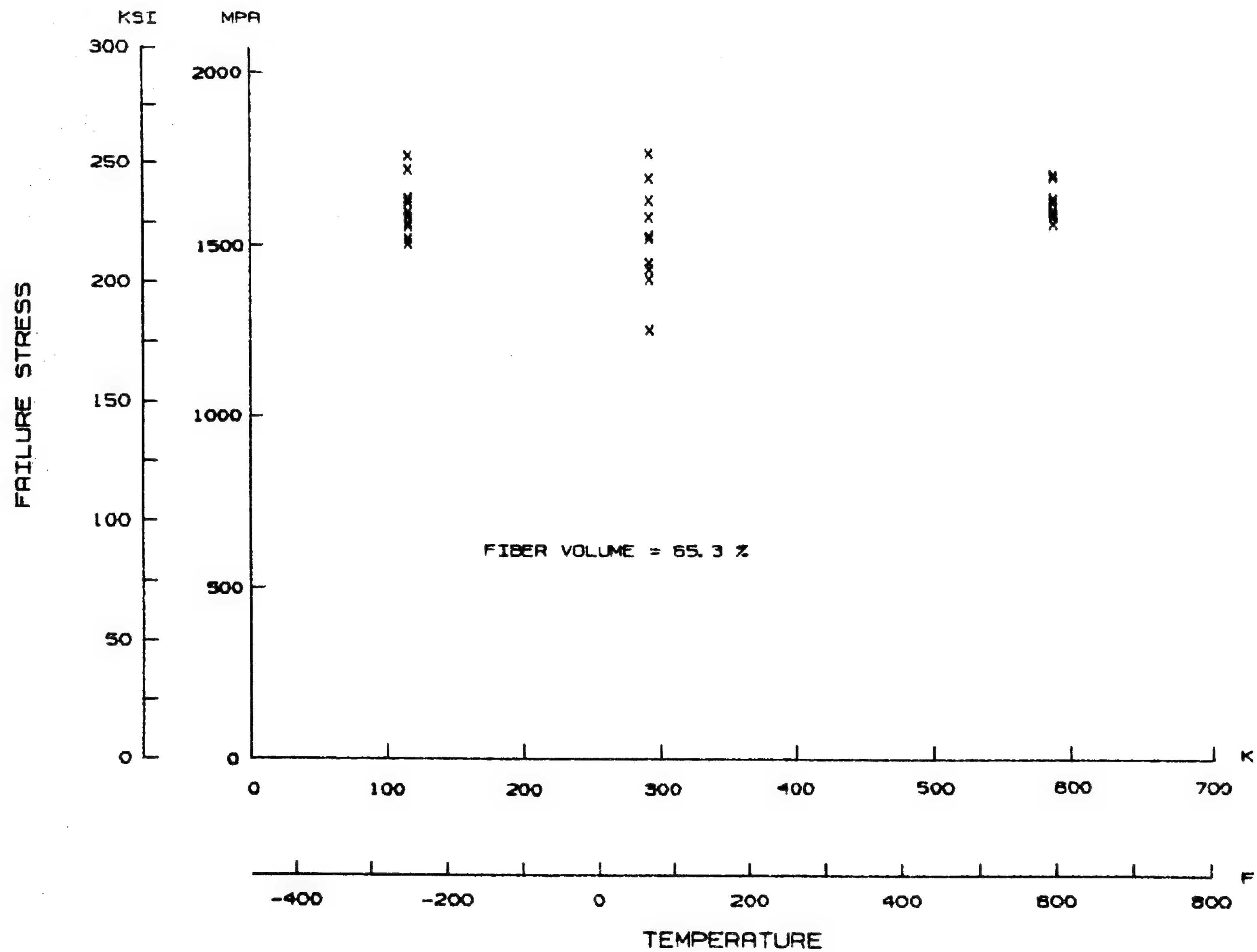


Figure 6.3-6: Celion 6000/PMR-15 Tension Tests $(0)_8$ Layup - Failure Stress

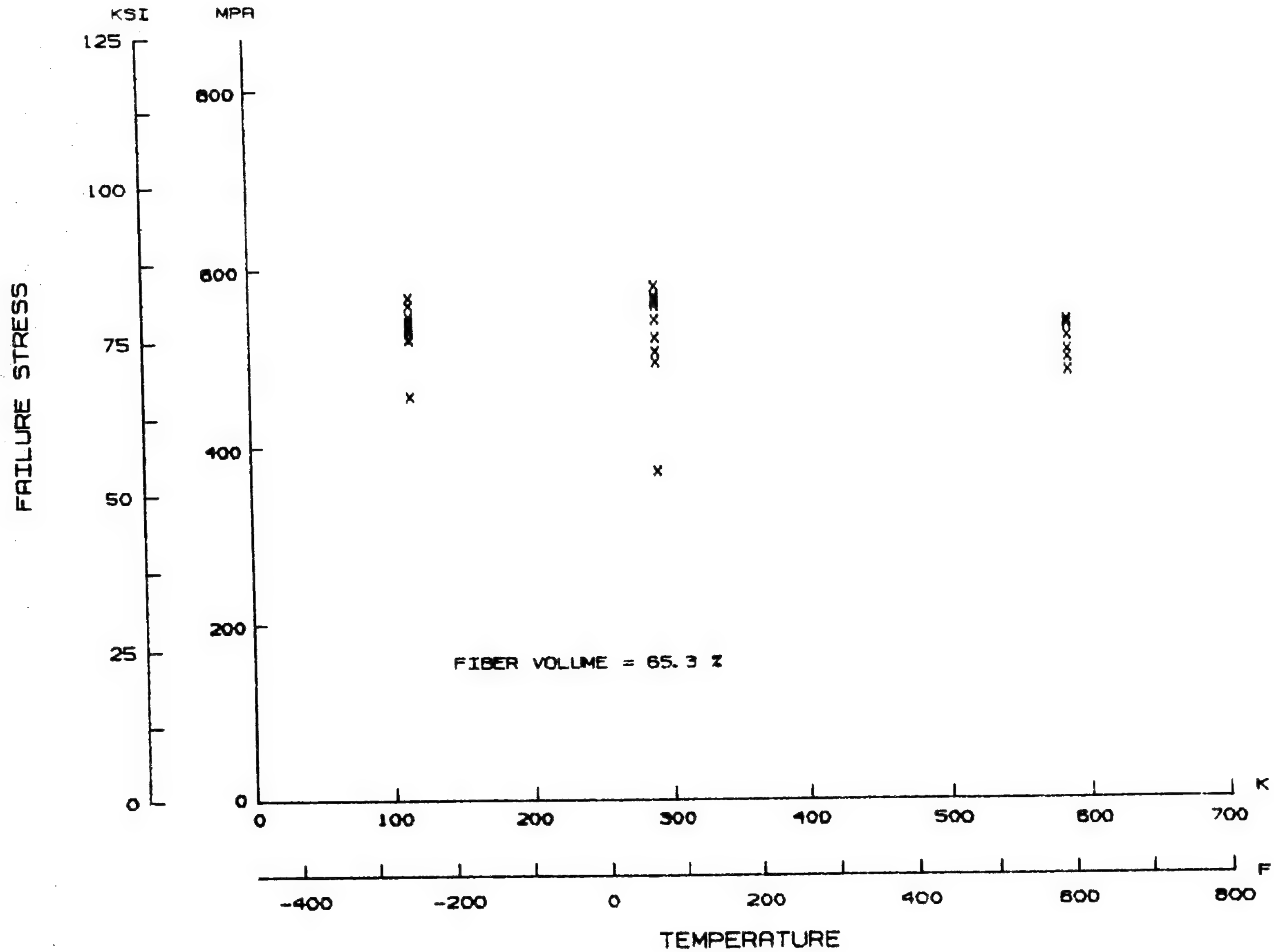


Figure 6.3-7: Celion 6000/PMR-15 Tension Tests $(0/+45/90/-45)_S$ Layup - Failure Stress

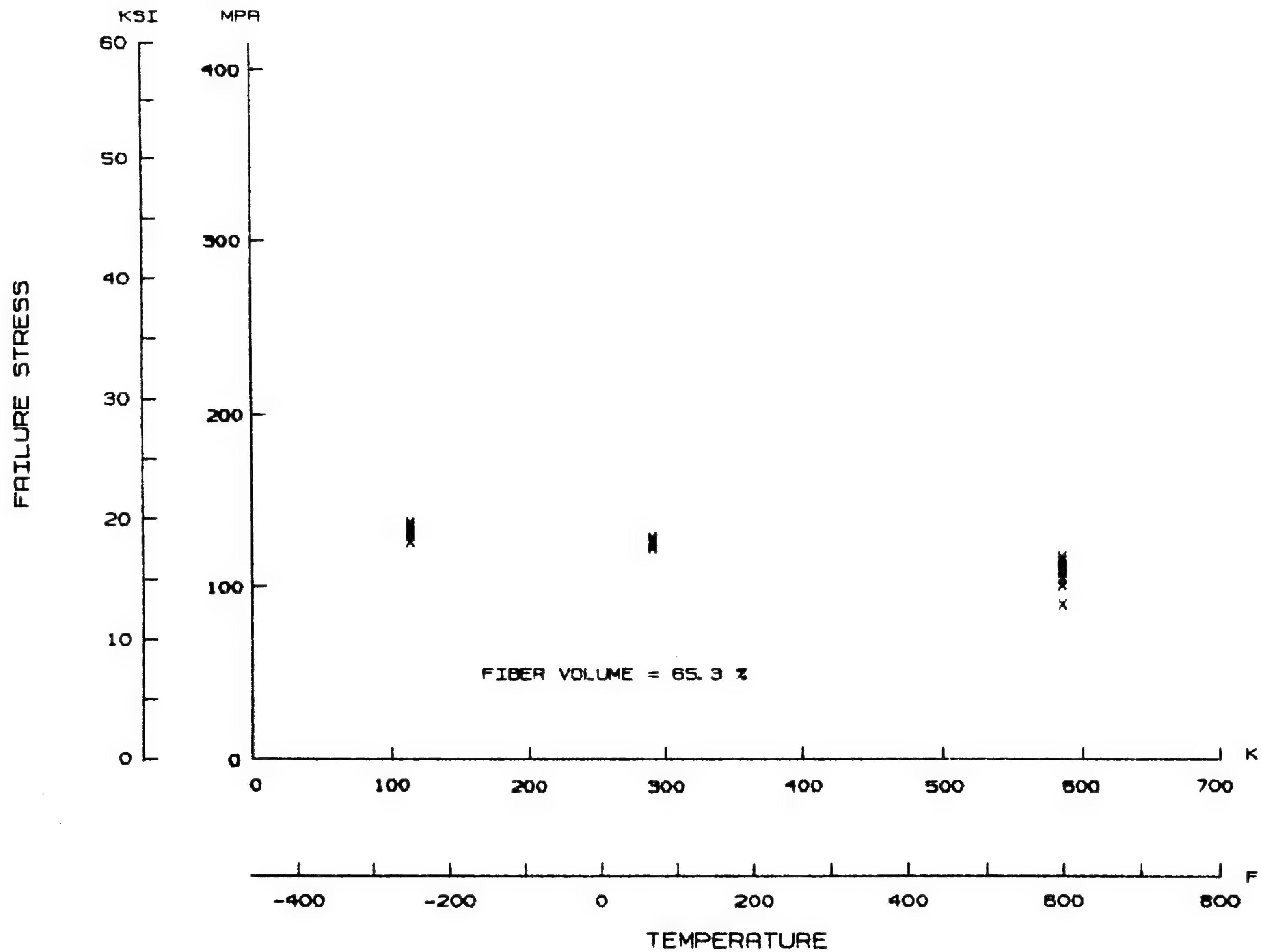


Figure 6.3-8: Celion 6000/PMR-15 Tension Tests $(\underline{+}45)_{2S}$ Layup - Failure Stress

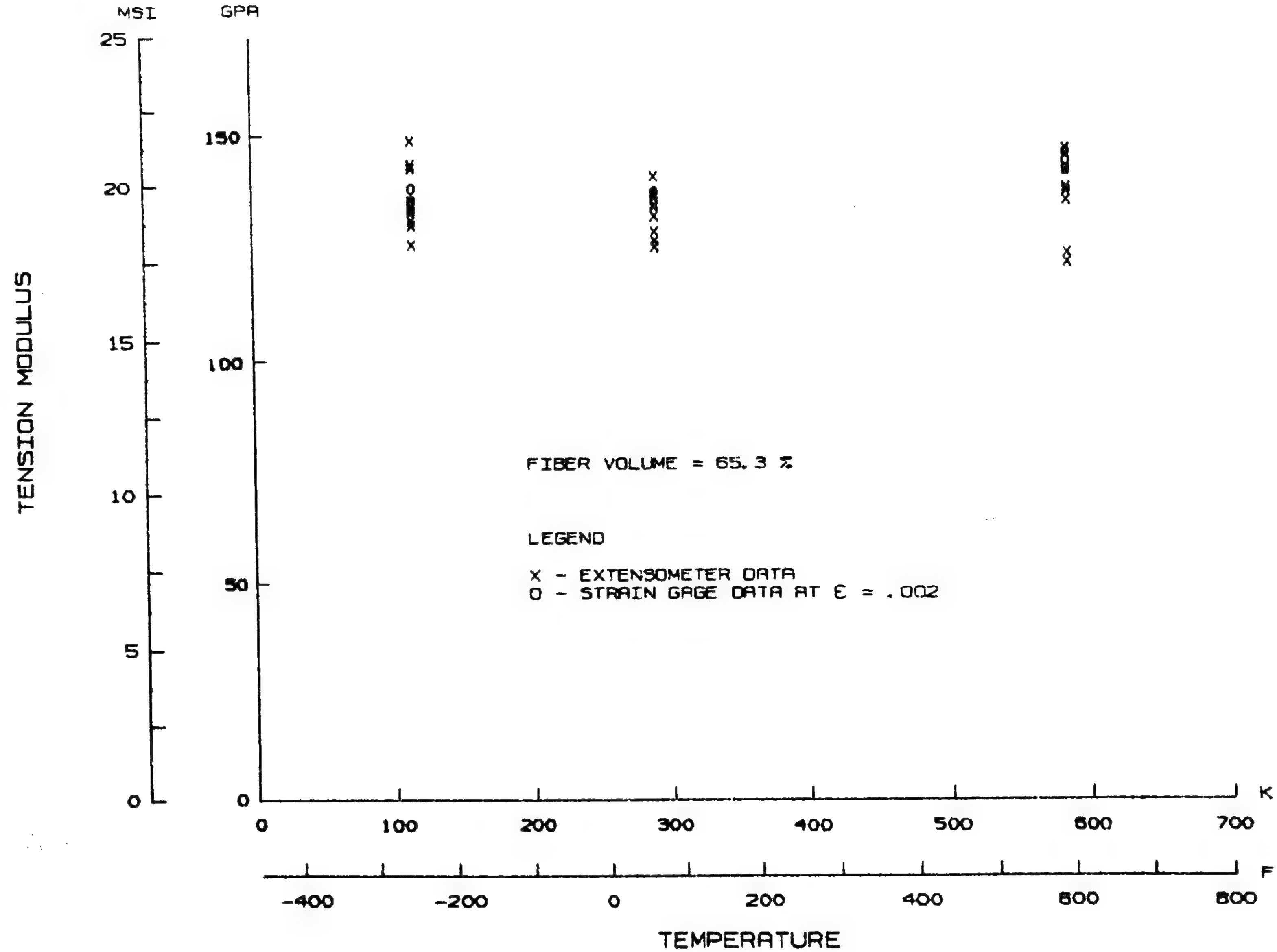


Figure 6.3-9: Celion 6000/PMR-15 Tension Tests $(0)_8$ Layup - Modulus

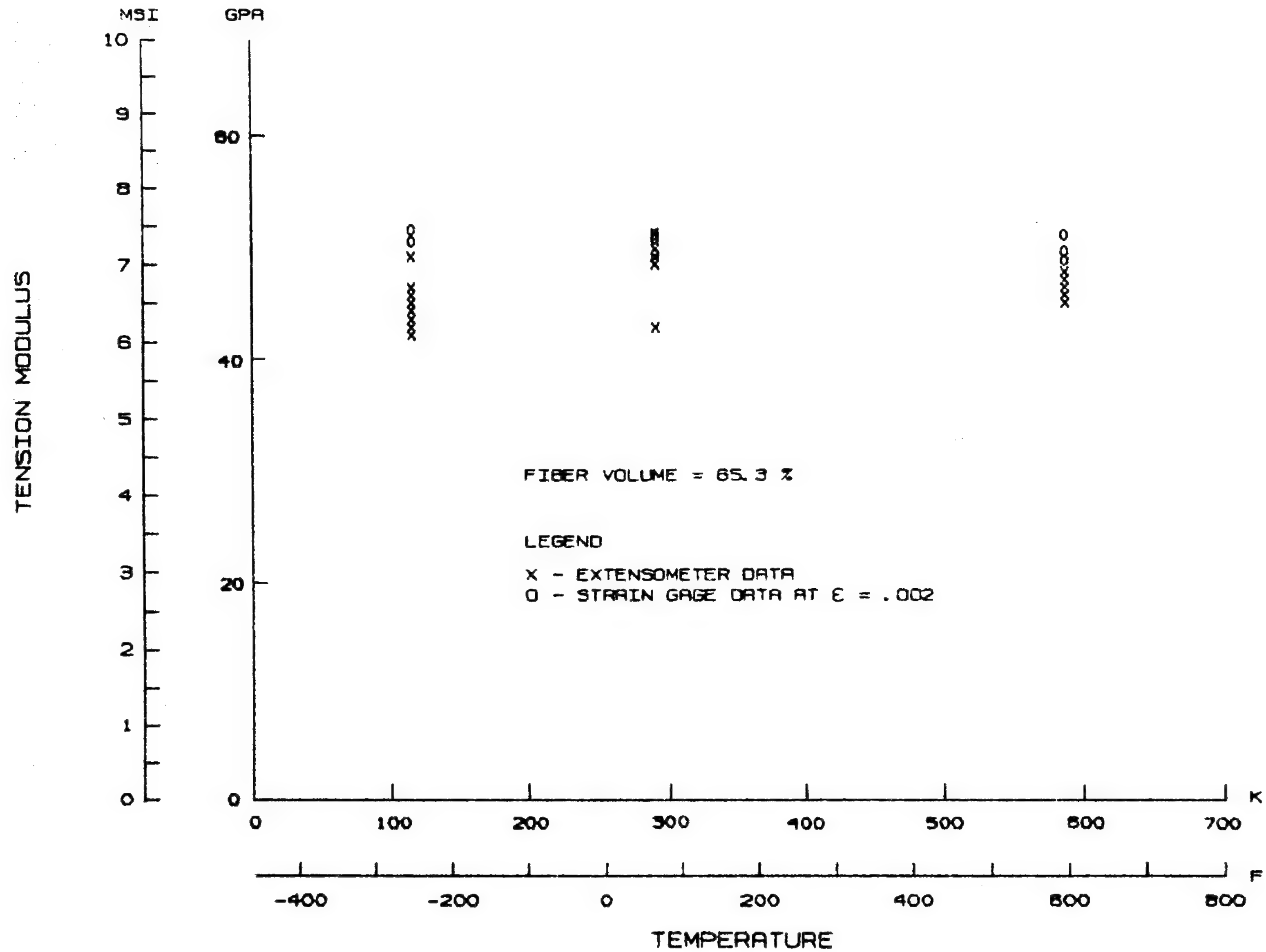


Figure 6.3-10: Celion 6000/PMR-15 Tension Tests $(0/+45/90/-45)_S$ Layup - Modulus

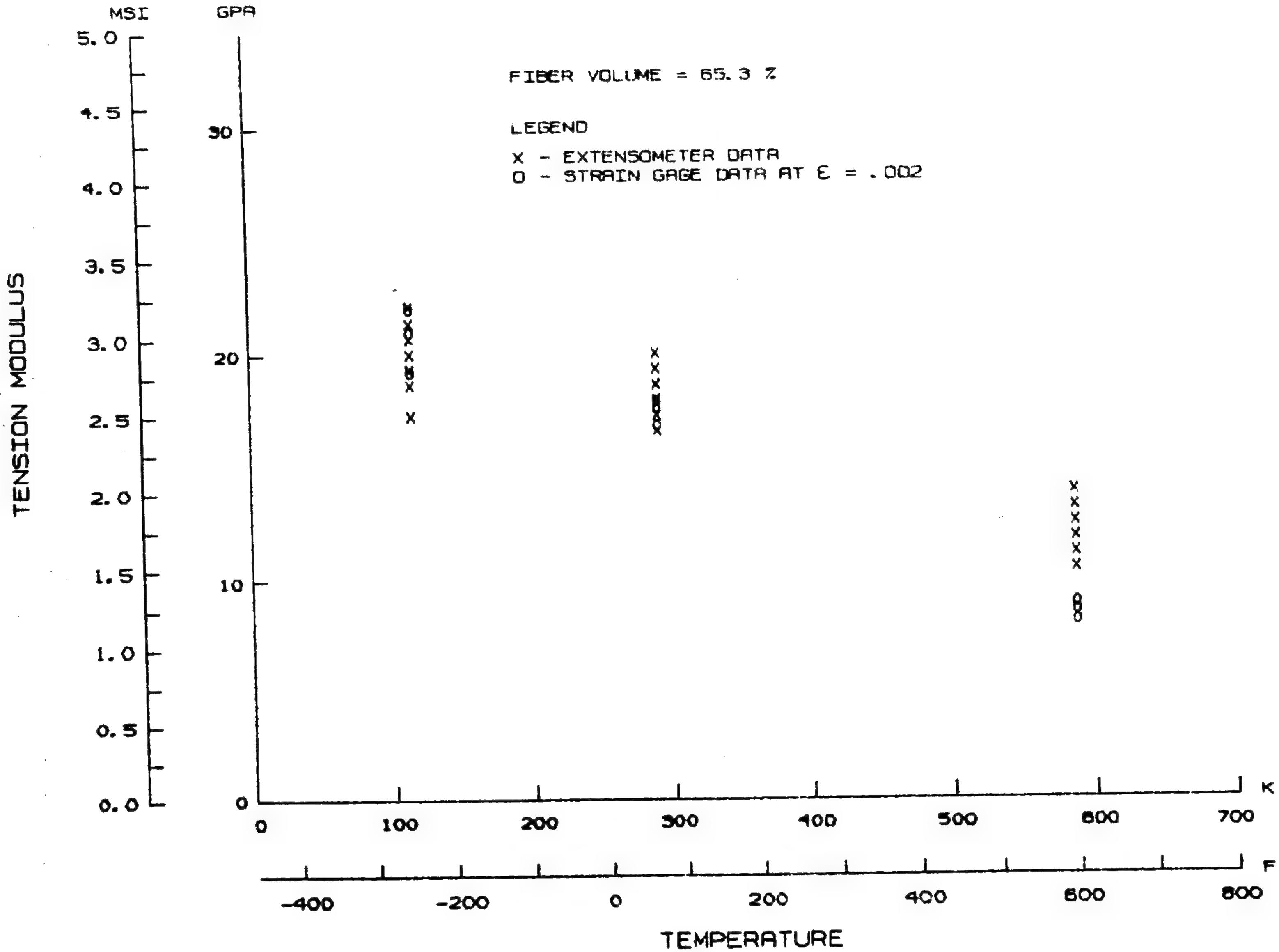


Figure 6.3-11: Celion 6000/PMR-15 Tension Tests $(\pm 45)_{2S}$ Layup - Modulus

6.4 Compression Tests

This section presents test procedures and test results for compression tests of $(0)_{16}$, $(0/+45/90/-45)_{2S}$ and $(\pm 45)_{4S}$ laminates.

6.4.1 Test Procedures

Compression tests (tests 4, 5, and 6 of Matrix 1A) were performed using an IITRI* test fixture furnished by NASA LaRC. A typical test setup is shown in Figure 6.4-1. Specimens were removed from the storage oven and installed in the IITRI fixture on a Baldwin universal test machine. The short specimen test section and constraints of the fixture prevented using extensometers; therefore, load versus strain was recorded only on strain gaged specimens. Where applicable, strain gage output was recorded using the automatic data aquisition system. Thermocouples were installed on the specimen test section and on the top and bottom portions of the test fixture to monitor temperature gradients. Only one thermocouple was used on the room temperature specimens to assure they had cooled to room temperature after removal from the storage oven. A cross head travel of 2.1 x 10^{-5} m/sec (.05 in/min) was applied and controlled using a potentiometer connected to the test machine.

6.4.2 Test Results

Test results are summarized in Tables 6.4-1 through 6.4-3. Typical failed specimens are shown in Figures 6.4-2 through 6.4-4.

Test results are plotted as functions of temperature in Figure 6.4-5 through 6.4-10. For all layups tested, compressive strength decreased

*IITRI: Illinois Institute of Technology Research Institute

with increasing temperature. For the $(0)_{16}$ laminates this may be because the matrix plays an important role in the stability of the fibers. For the $(0/+45/90/-45)_{2S}$ and $(\pm 45)_{4S}$ laminates this behavior is explained by the matrix dominated nature of these laminates and by the behavior of the $(0)_{16}$ laminates.

Physical constraints prevented using an extensometer on the compression tests, therefore, modulus data were only obtained on the strain gaged specimens. Strain to failure is not reported because variations in back-to-back strain gages were large at failure and many strain gages failed before ultimate load was achieved. Because of the limited data, results are only indicative of performance trends. In addition, there were some anomalies in the back-to-back strain gage output. At a strain level of .2%, incremental changes in back-to-back longitudinal strain gages varied by as little as 0.7% and by as much as 59% with the average variation being 19%. Back-to-back strain gage variation may have been caused by specimen curvature and/or fixture misalignment. There was no correlation between back-to-back strain gage variation and any premature specimen failure.

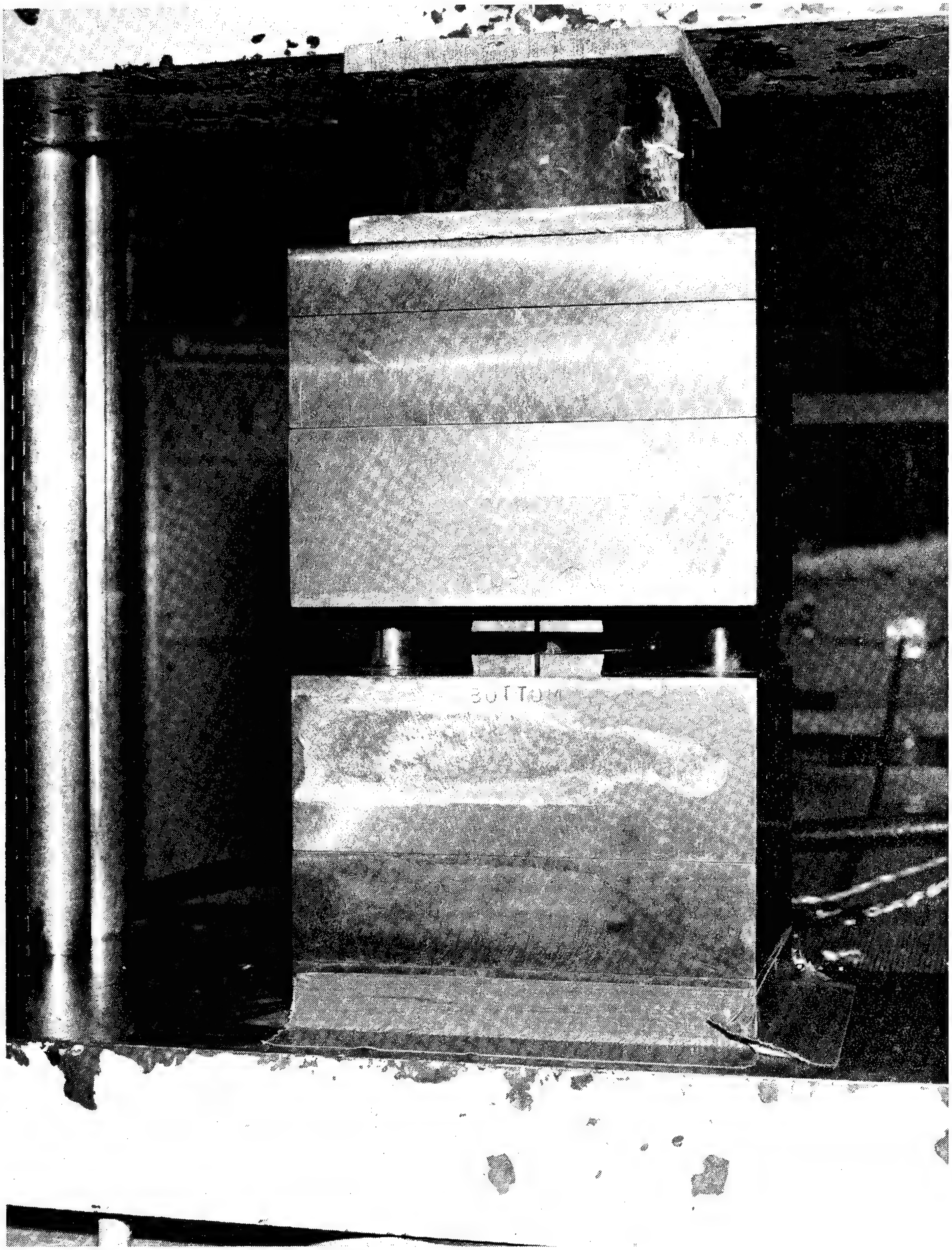


Figure 6.4-1: ITTRI Compression Test Setup

TABLE 6.4-1. CELION 6000/PMR-15 DESIGN ALLOWABLES COMPRESSION TESTS [0]16 LAYUP

(a) SI UNITS

SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	STRAIN GAGE DATA ϵ = .002 APPARENT COMPRESSION MODULUS GPA	APPARENT POISSON'S RATIO
1A-4-1	2.21	12.68	116.	32650.	1165.		
1A-4-2	2.21	12.68	116.	39990.	1427.		
1A-4-3	2.29	12.67	116.	35897.	1234.		
1A-4-4	2.21	12.71	116.	39678.	1413.		
1A-4-5	2.32	12.68	116.	31760.	1076.		
1A-4-6	2.27	12.69	116.	36742.	1276.		
1A-4-7	2.19	12.68	116.	38744.	1393.		
1A-4-8	2.22*	12.73	116.	33228.	1179.	NO DATA	NO DATA
1A-4-9	2.22*	12.72	116.	34518.	1227.	134.**	.471
1A-4-10	2.22*	12.71	116.	31916.	1131.	129.	.280
1A-4-11	2.21	12.70	294.	33584.	1200.		
1A-4-12	2.27	12.69	294.	22730.	786.		
1A-4-13	2.22	12.67	294.	19661.	696.		
1A-4-14	2.22	12.69	294.	28135.	1000.		
1A-4-15	2.17	12.68	294.	26778.	972.		
1A-4-16	2.21	12.69	294.	27646.	986.		
1A-4-17	2.35	12.70	294.	26823.	903.		
1A-4-18	2.22*	12.72	294.	33273.	1179.	122.	.326
1A-4-19	2.22*	12.71	294.	30515.	1082.	121.	.336
1A-4-20	2.22*	12.71	294.	25800.	917.	NO DATA	NO DATA
1A-4-21	1.88	12.66	589.	16503.	692.		
1A-4-22	2.19	12.66	589.	13745.	496.		
1A-4-23	2.34	12.64	589.	14902.	503.		
1A-4-24	2.18	12.67	589.	14412.	523.		
1A-4-25	2.24	12.67	589.	15925.	561.		
1A-4-26	2.18	12.64	589.	14190.	514.		
1A-4-27	2.21	12.66	589.	15346.	549.		
1A-4-28	2.22*	12.73	589.	16814.	596.	NO DATA	NO DATA
1A-4-29	2.22*	12.72	589.	14902.	528.	119.**	.301***
1A-4-30	2.22*	12.71	589.	14857.	527.	NO DATA	NO DATA

* ESTIMATED
** 1 LONGITUDINAL STRAIN GAGE FAULTY
*** 1 TRANSVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.4-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	STRAIN GAGE DATA ε = .002 APPARENT COMPRESSION MODULUS MSI	APPARENT POISSON'S RATIO
1A-4-1	.0870	.4994	-250.	7340.	169.0		
1A-4-2	.0870	.4992	-250.	8990.	207.0		
1A-4-3	.0901	.4990	-250.	8070.	179.0		
1A-4-4	.0870	.5002	-250.	8920.	205.0		
1A-4-5	.0915	.4992	-250.	7140.	156.0		
1A-4-6	.0894	.4995	-250.	8260.	185.0		
1A-4-7	.0863	.4993	-250.	8710.	202.0		
1A-4-8	.0873*	.5011	-250.	7470.	171.0	NO DATA	NO DATA
1A-4-9	.0873*	.5007	-250.	7760.	178.0	19.5**	.471
1A-4-10	.0873*	.5005	-250.	7175.	164.0	18.7	.280
1A-4-11	.0870	.4999	70.	7550.	174.0		
1A-4-12	.0895	.4998	70.	5110.	114.0		
1A-4-13	.0873	.4990	70.	4420.	101.0		
1A-4-14	.0874	.4998	70.	6325.	145.0		
1A-4-15	.0855	.4993	70.	6020.	141.0		
1A-4-16	.0871	.4995	70.	6215.	143.0		
1A-4-17	.0924	.5000	70.	6030.	131.0		
1A-4-18	.0873*	.5008	70.	7480.	171.0	17.7	.326
1A-4-19	.0873*	.5005	70.	6860.	157.0	17.6	.336
1A-4-20	.0873*	.5003	70.	5800.	133.0	NO DATA	NO DATA
1A-4-21	.0742	.4984	600.	3710.	100.3		
1A-4-22	.0861	.4983	600.	3090.	72.0		
1A-4-23	.0923	.4977	600.	3350.	72.9		
1A-4-24	.0857	.4987	600.	3240.	75.8		
1A-4-25	.0882	.4987	600.	3580.	81.4		
1A-4-26	.0860	.4975	600.	3190.	74.6		
1A-4-27	.0870	.4984	600.	3450.	79.6		
1A-4-28	.0873*	.5013	600.	3780.	86.4	NO DATA	NO DATA
1A-4-29	.0873*	.5007	600.	3350.	76.6	17.3**	.301***
1A-4-30	.0873*	.5002	600.	3340.	76.5	NO DATA	NO DATA

* ESTIMATED
** 1 LONGITUDINAL STRAIN GAGE FAULTY
*** 1 TRANSVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.4-2. CELION 6000/PMR-15 DESIGN ALLOWABLES COMPRESSION TESTS [0/+45/90/-45]2S LAYUP

(a) SI UNITS

SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	STRAIN GAGE DATA ϵ = .002 APPARENT COMPRESSION MODULUS GPA	APPARENT POISSON'S RATIO
1A-5-1	2.11	12.67	116.	17570.	657.		
1A-5-2	2.11	12.65	116.	17482.	654.		
1A-5-3	2.11	12.62	116.	13434.	505.		
1A-5-4	2.27	12.70	116.	16058.	556.		
1A-5-5	2.25	12.68	116.	17126.	601.		
1A-5-6	2.27	12.70	116.	15168.	527.		
1A-5-7	2.25	12.69	116.	13878.	486.		
1A-5-8	2.21*	12.69	116.	19305.	688.	57.2	.376
1A-5-9	2.21*	12.72	116.	22819.	812.	63.2	.395
1A-5-10	2.21*	12.73	116.	18393.	654.	61.3	.292
1A-5-11	2.23	12.66	294.	15524.	550.		
1A-5-12	2.26	12.69	294.	15858.	553.		
1A-5-13	2.25	12.68	294.	15747.	552.		
1A-5-14	2.24	12.71	294.	16837.	591.		
1A-5-15	2.21	12.66	294.	14813.	530.		
1A-5-16	2.19	12.71	294.	16280.	585.		
1A-5-17	2.28	12.67	294.	16369.	566.		
1A-5-18	2.21*	12.71	294.	13789.	491.	40.5	.309
1A-5-19	2.21*	12.75	294.	14190.	504.	40.9	.321
1A-5-20	2.21*	12.71	294.	14768.	525.	44.1	.328
1A-5-21	2.25	12.67	589.	11521.	403.		
1A-5-22	2.27	12.69	589.	11343.	394.		
1A-5-23	2.20	12.70	589.	9564.	342.		
1A-5-24	2.16	12.70	589.	10542.	384.		
1A-5-25	2.25	12.70	589.	11610.	405.		
1A-5-26	2.20	12.70	589.	10231.	366.		
1A-5-31	2.25	12.72	589.	10542.	369.		
1A-5-28	2.21*	12.72	589.	10587.	376.	48.5	.366
1A-5-29	2.21*	12.72	589.	10676.	380.	NO DATA	NO DATA
1A-5-30	2.21*	12.72	589.	10676.	380.	52.8	.396

* ESTIMATED

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.4-2. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	STRAIN GAGE DATA ε = .002 APPARENT COMPRESSION MODULUS MSI	APPARENT POISSON'S RATIO
1A-5-1	.0831	.4990	-250.	3950.	95.3		
1A-5-2	.0832	.4980	-250.	3930.	94.9		
1A-5-3	.0830	.4968	-250.	3020.	73.2		
1A-5-4	.0895	.4999	-250.	3610.	80.7		
1A-5-5	.0885	.4993	-250.	3850.	87.1		
1A-5-6	.0893	.5000	-250.	3410.	76.4		
1A-5-7	.0885	.4998	-250.	3120.	70.5		
1A-5-8	.0870*	.4996	-250.	4340.	99.8	8.29	.376
1A-5-9	.0870*	.5006	-250.	5130.	117.8	9.17	.395
1A-5-10	.0870*	.5011	-250.	4135.	94.8	8.89	.292
1A-5-11	.0877	.4986	70.	3490.	79.8		
1A-5-12	.0890	.4997	70.	3565.	80.2		
1A-5-13	.0885	.4994	70.	3540.	80.1		
1A-5-14	.0883	.5004	70.	3785.	85.7		
1A-5-15	.0870	.4984	70.	3330.	76.8		
1A-5-16	.0862	.5004	70.	3660.	84.9		
1A-5-17	.0898	.4989	70.	3680.	82.1		
1A-5-18	.0870*	.5004	70.	3100.	71.2	5.88	.309
1A-5-19	.0870*	.5019	70.	3190.	73.1	5.93	.321
1A-5-20	.0870*	.5005	70.	3320.	76.2	6.39	.328
1A-5-21	.0887	.4990	600.	2590.	58.5		
1A-5-22	.0893	.4996	600.	2550.	57.2		
1A-5-23	.0867	.4999	600.	2150.	49.6		
1A-5-24	.0851	.5000	600.	2370.	55.7		
1A-5-25	.0886	.5000	600.	2610.	58.7		
1A-5-26	.0867	.5000	600.	2300.	53.1		
1A-5-31	.0885	.5006	600.	2370.	53.5		
1A-5-28	.0870*	.5006	600.	2380.	54.6	7.04	.366
1A-5-29	.0870*	.5006	600.	2400.	55.1	NO DATA	NO DATA
1A-5-30	.0870*	.5008	600.	2400.	55.1	7.66	.396

* ESTIMATED

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.4-3. CELION 6000/PMR-15 DESIGN ALLOWABLES COMPRESSION TESTS [+-45]4S LAYUP

(a) SI UNITS

SPECIMEN	THICKNESS MM	WIDTH MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	STRAIN GAGE DATA ε = .002 APPARENT COMPRESSION MODULUS GPA	APPARENT POISSON'S RATIO
1A-6-1	2.12	12.73	116.	5124.	190.		
1A-6-2	2.08	12.66	116.	5231.	199.		
1A-6-3	2.16	12.69	116.	5587.	204.		
1A-6-4	2.23	12.69	116.	5694.	201.		
1A-6-5	2.28	12.70	116.	5338.	185.		
1A-6-6	2.19	12.70	116.	5276.	190.		
1A-6-7	2.14	12.74	116.	5596.	205.		
1A-6-8	2.15*	12.73	116.	7882.	288.	30.0	.659
1A-6-9	2.15*	12.73	116.	7713.	282.	17.7**	.684***
1A-6-10	2.15*	12.71	116.	10102.	370.	25.1	.650
1A-6-11	2.12	12.72	294.	4782.	177.		
1A-6-12	2.26	12.72	294.	4448.	154.		
1A-6-13	2.18	12.72	294.	4350.	157.		
1A-6-14	2.21	12.66	294.	4613.	165.		
1A-6-15	1.96	12.71	294.	4951.	199.		
1A-6-16	2.19	12.71	294.	4359.	157.		
1A-6-17	2.24	12.72	294.	4680.	164.		
1A-6-18	2.15*	12.73	294.	4564.	167.	9.3	.476
1A-6-19	2.15*	12.72	294.	4466.	163.	12.5**	.712
1A-6-20	2.15*	12.71	294.	4964.	182.	15.2	.774
1A-6-21	2.09	12.69	589.	3114.	117.		
1A-6-22	2.20	12.69	589.	2713.	97.		
1A-6-23	2.18	12.69	589.	2829.	102.		
1A-6-24	2.04	12.68	589.	2793.	108.		
1A-6-25	1.99	12.69	589.	2909.	115.		
1A-6-26	2.17	12.69	589.	3229.	117.		
1A-6-27	2.11	12.67	589.	1646.	62.		
1A-6-28	2.15*	12.72	589.	2455.	90.	9.3	.923
1A-6-29	2.15*	12.73	589.	2696.	99.	7.7	.940
1A-6-30	2.15*	12.72	589.	2758.	101.	7.4	.635

* ESTIMATED
** 1 LONGITUDINAL STRAIN GAGE FAULTY
*** 1 TRANSVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.4-3. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	WIDTH IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	STRAIN GAGE DATA ϵ = .002 APPARENT COMPRESSION MODULUS MSI	APPARENT POISSON'S RATIO
1A-6-1	.0835	.5013	-250.	1152.	27.5		
1A-6-2	.0818	.4984	-250.	1176.	28.8		
1A-6-3	.0849	.4998	-250.	1256.	29.6		
1A-6-4	.0877	.4995	-250.	1280.	29.2		
1A-6-5	.0897	.4999	-250.	1200.	26.8		
1A-6-6	.0862	.5000	-250.	1186.	27.5		
1A-6-7	.0843	.5017	-250.	1258.	29.7		
1A-6-8	.0846*	.5011	-250.	1772.	41.8	4.35	.659
1A-6-9	.0846*	.5013	-250.	1734.	40.9	2.56**	.684***
1A-6-10	.0846*	.5004	-250.	2271.	53.6	3.64	.650
1A-6-11	.0835	.5009	70.	1075.	25.7		
1A-6-12	.0890	.5007	70.	1000.	22.4		
1A-6-13	.0857	.5007	70.	978.	22.8		
1A-6-14	.0872	.4984	70.	1037.	23.9		
1A-6-15	.0772	.5005	70.	1113.	28.8		
1A-6-16	.0861	.5005	70.	980.	22.7		
1A-6-17	.0881	.5007	70.	1052.	23.8		
1A-6-18	.0846*	.5012	70.	1026.	24.2	1.35	.476
1A-6-19	.0846*	.5009	70.	1004.	23.7	1.81**	.712
1A-6-20	.0846*	.5005	70.	1116.	26.4	2.21	.774
1A-6-21	.0822	.4997	600.	700.	17.0		
1A-6-22	.0865	.4997	600.	610.	14.1		
1A-6-23	.0859	.4996	600.	636.	14.8		
1A-6-24	.0802	.4993	600.	628.	15.7		
1A-6-25	.0784	.4996	600.	654.	16.7		
1A-6-26	.0853	.4996	600.	726.	17.0		
1A-6-27	.0831	.4990	600.	370.	8.9		
1A-6-28	.0846*	.5007	600.	552.	13.0	1.35	.923
1A-6-29	.0846*	.5012	600.	606.	14.3	1.11	.940
1A-6-30	.0846*	.5008	600.	620.	14.6	1.08	.635

* ESTIMATED
** 1 LONGITUDINAL STRAIN GAGE FAULTY
*** 1 TRANSVERSE STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

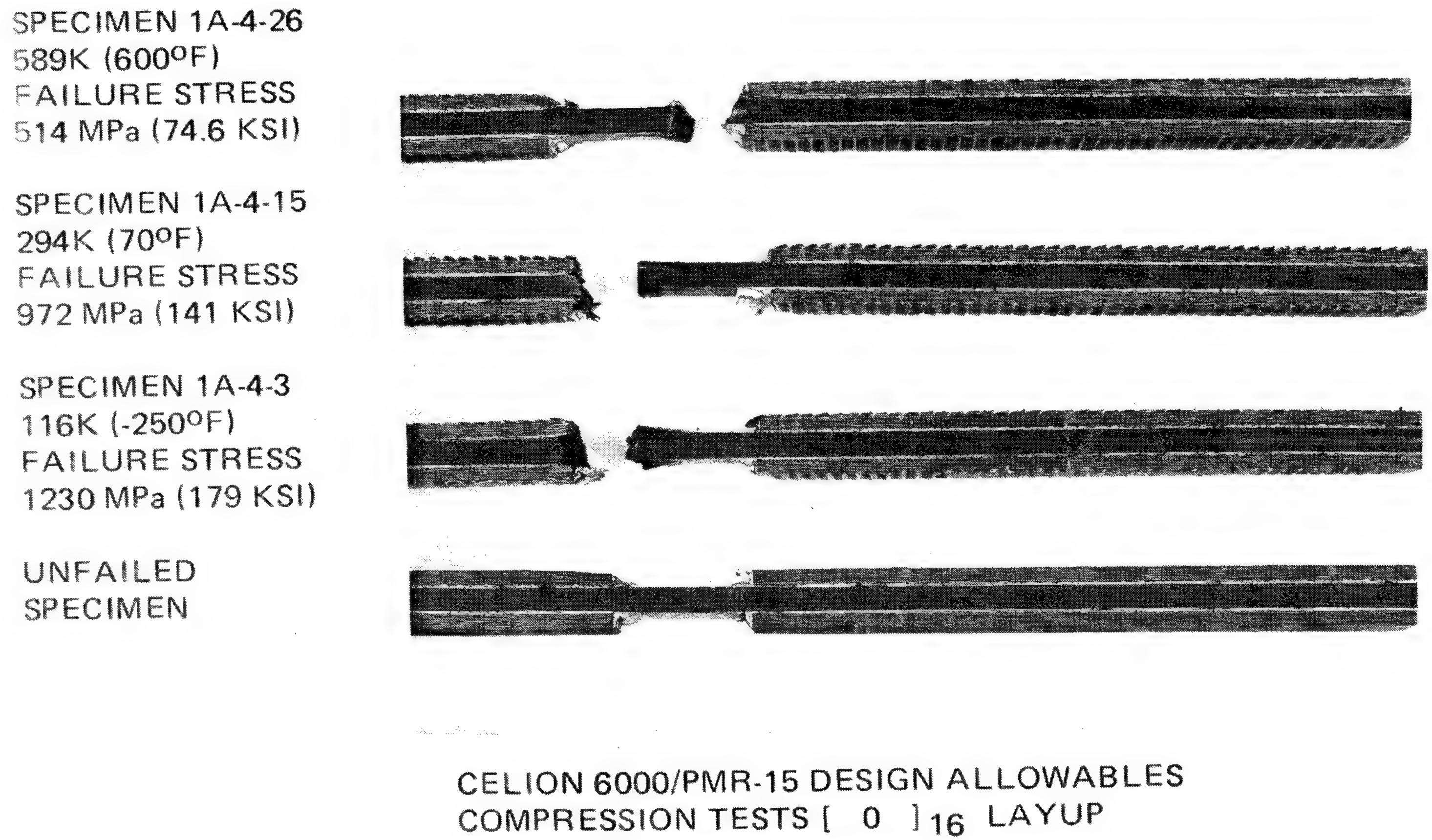


Figure 6.4-2: Celion 6000/PMR-15 Design Allowables Compression Tests $[0]_{16}$ Layup - Failed Specimens

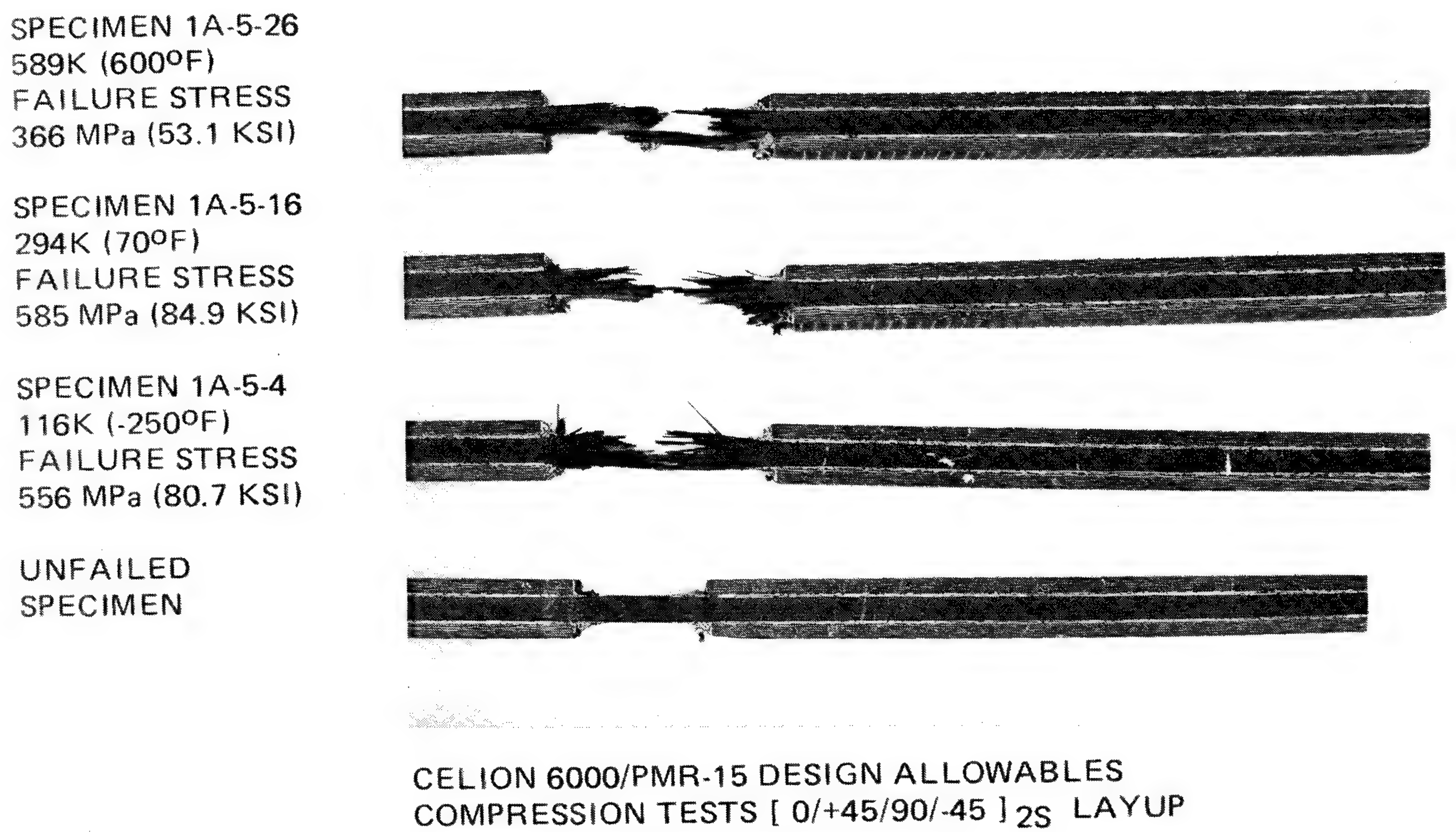


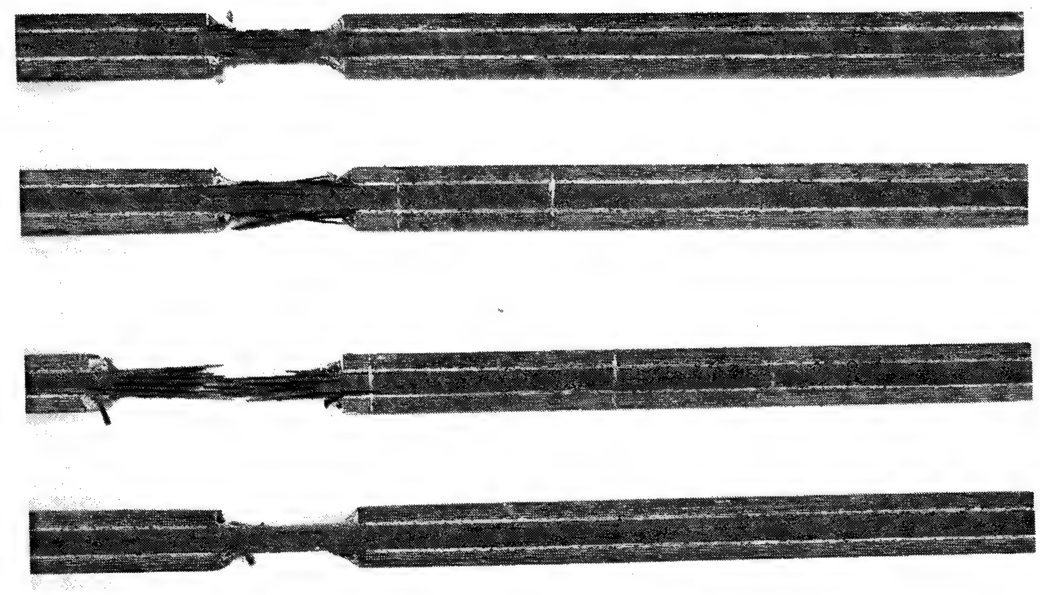
Figure 6.4-3: Celion 6000/PMR-15 Design Allowables Compression Tests $[0/+45/90/-45]_{2S}$ Layup - Failed Specimens

SPECIMEN 1A-6-23
589K (600°F)
FAILURE STRESS
102 MPa (14.8 KSI)

SPECIMEN 1A-6-14
294K (70°F)
FAILURE STRESS
165 MPa (23.9 KSI)

SPECIMEN 1A-6-2
116K (-250°F)
FAILURE STRESS
199 MPa (28.8 KSI)

UNFAILED
SPECIMEN



CELION 6000/PMR-15 DESIGN ALLOWABLES
COMPRESSION TESTS [± 45]$_{4S}$ LAYUP

Figure 6.4-4: Celion 6000/PMR-15 Design Allowables Compression Tests $[\pm 45]_{4S}$ Layup - Failed Specimens

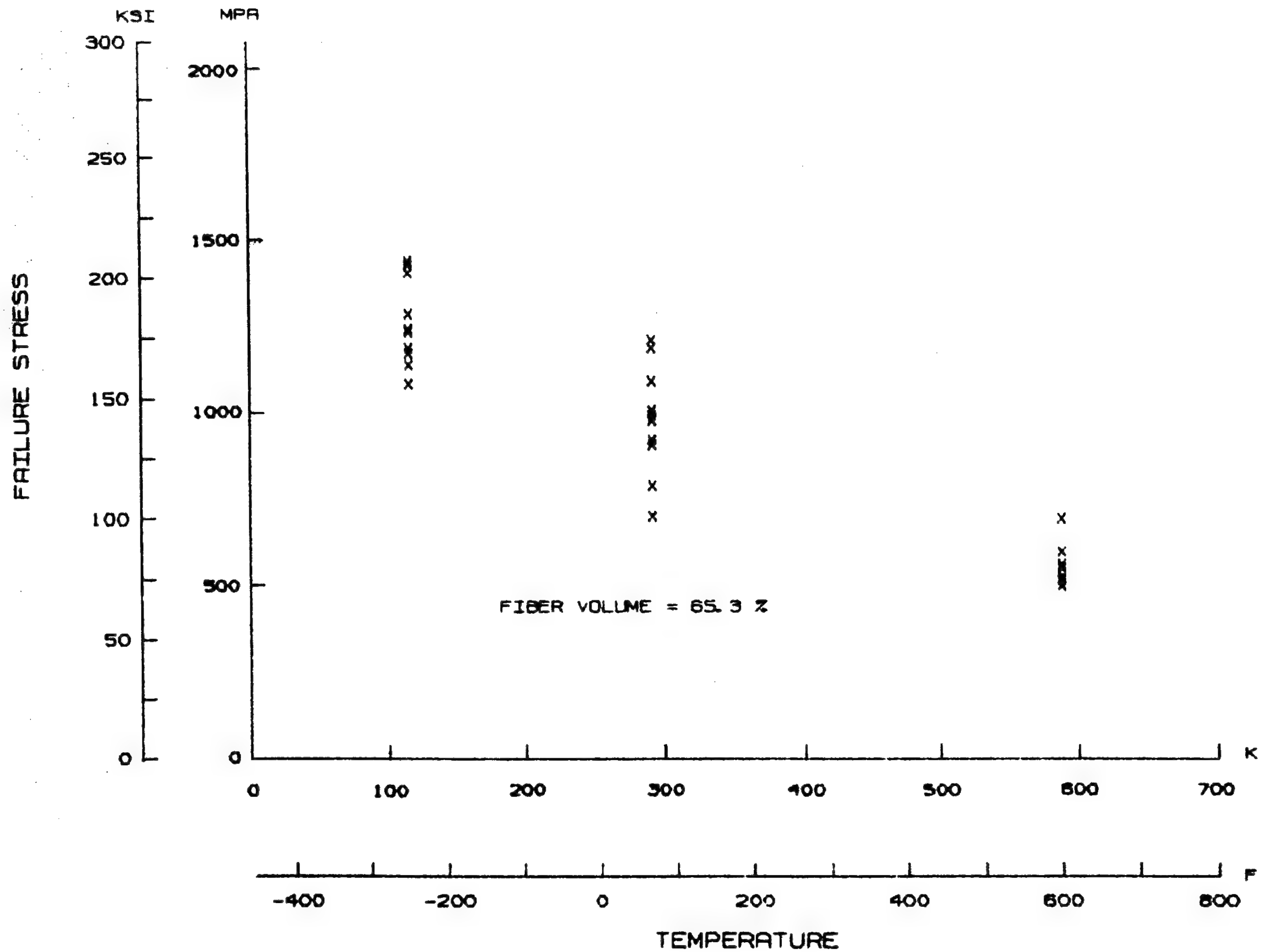


Figure 6.4-5: Celion 6000/PMR-15 Compression Tests $(0)_{16}$ - Failure Stress

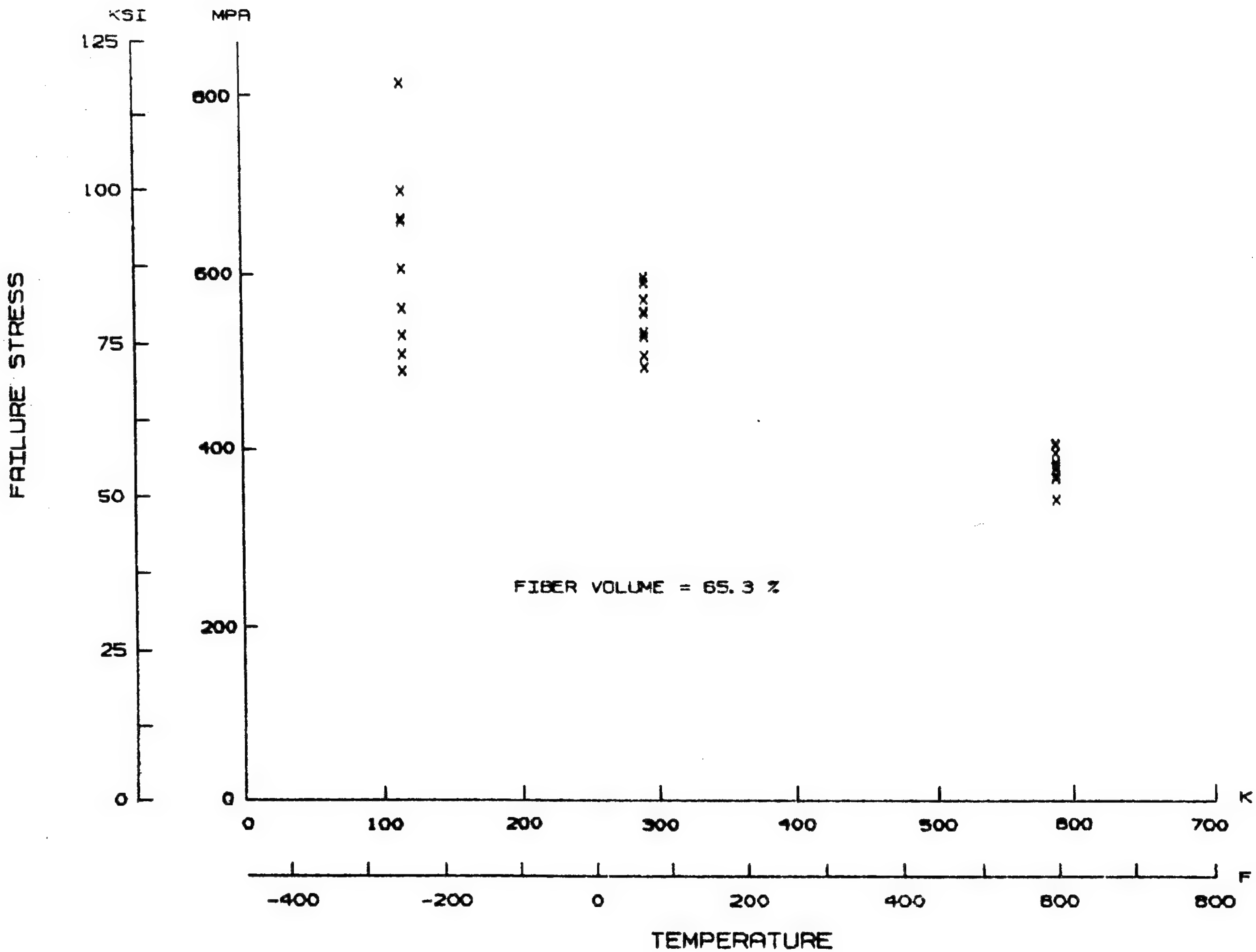


Figure 6.4-6: Celion 6000/PMR-15 Compression Tests $(0/+45/90/-45)_{2S}$ - Failure Stress

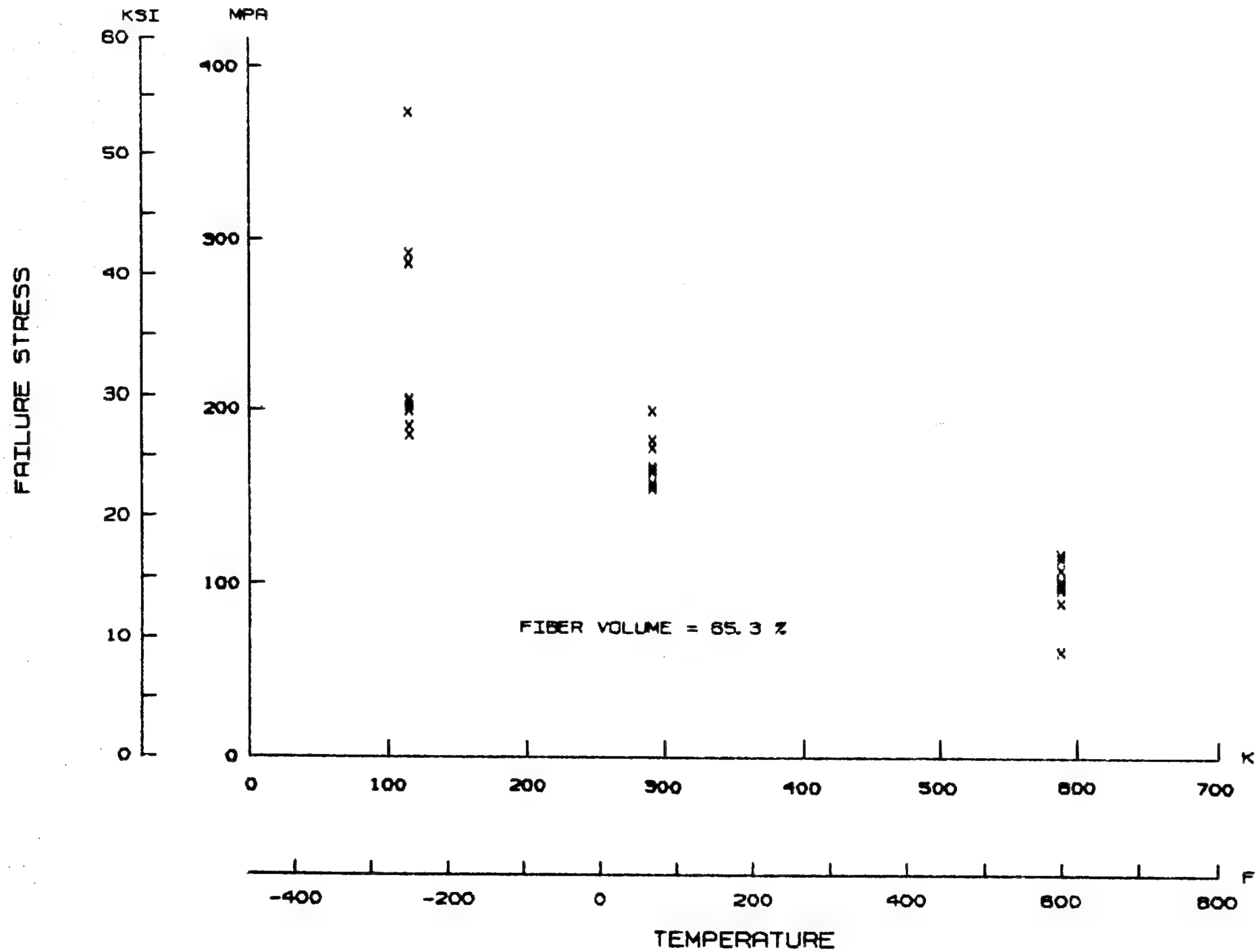


Figure 6.4-7: Celion 6000/PMR-15 Compression Tests $(\pm 45)_{4S}$ - Failure Stress

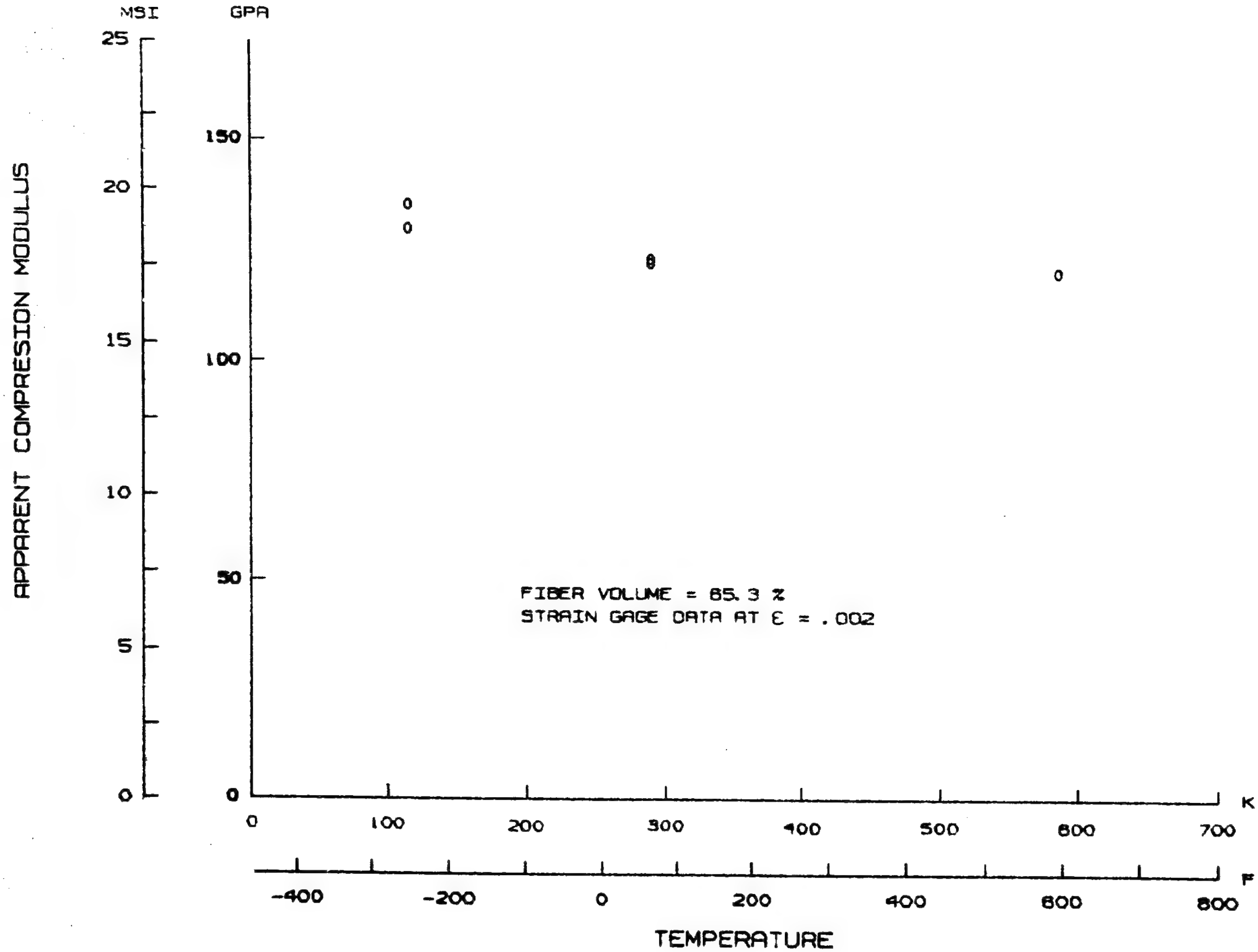


Figure 6.4-8: Celion 6000/PMR-15 Compression Tests $(0)_{16}$ - Modulus

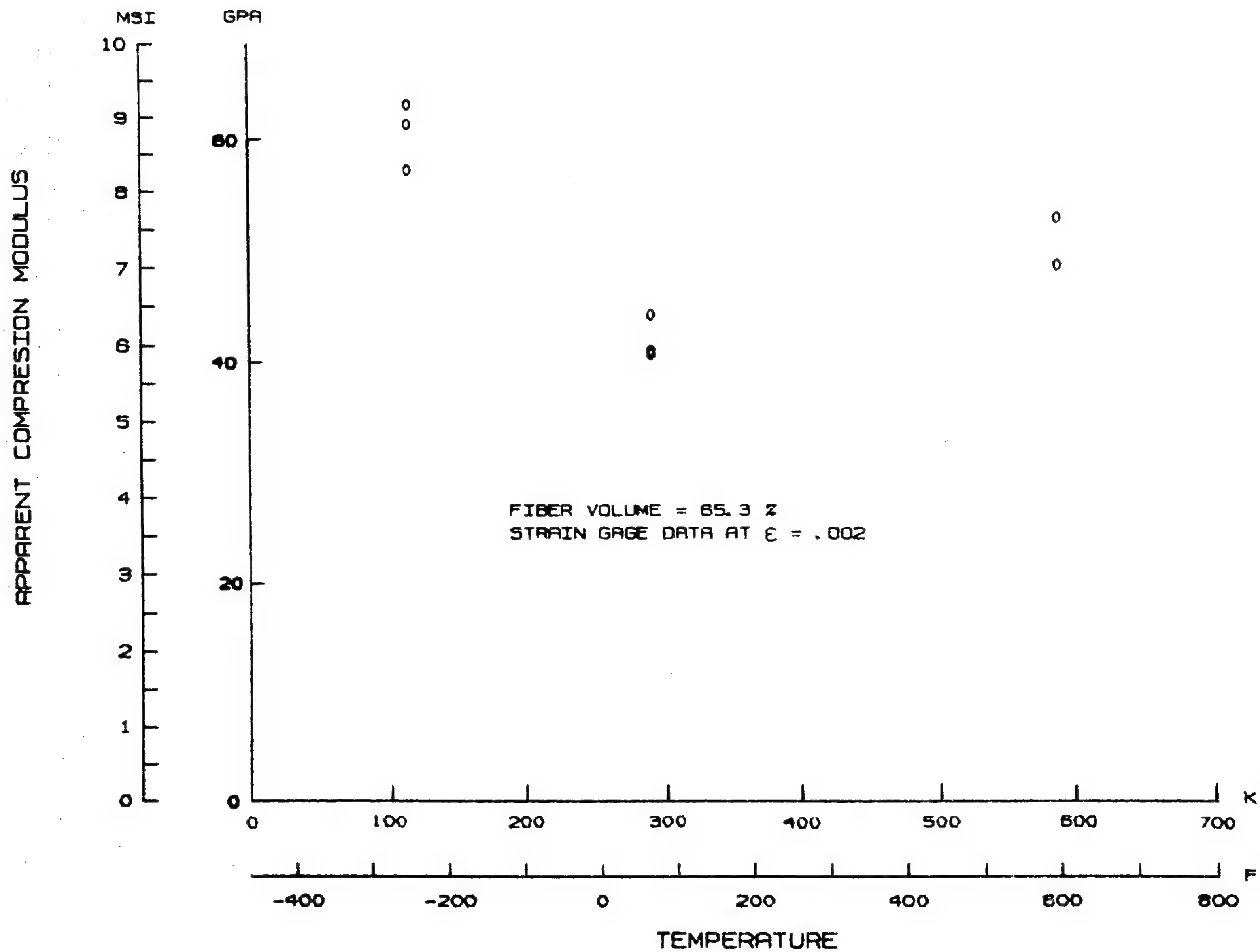


Figure 6.4-9: Celion 6000/PMR-15 Compression Tests $(0/+45/90/-45)_{2S}$ - Modulus

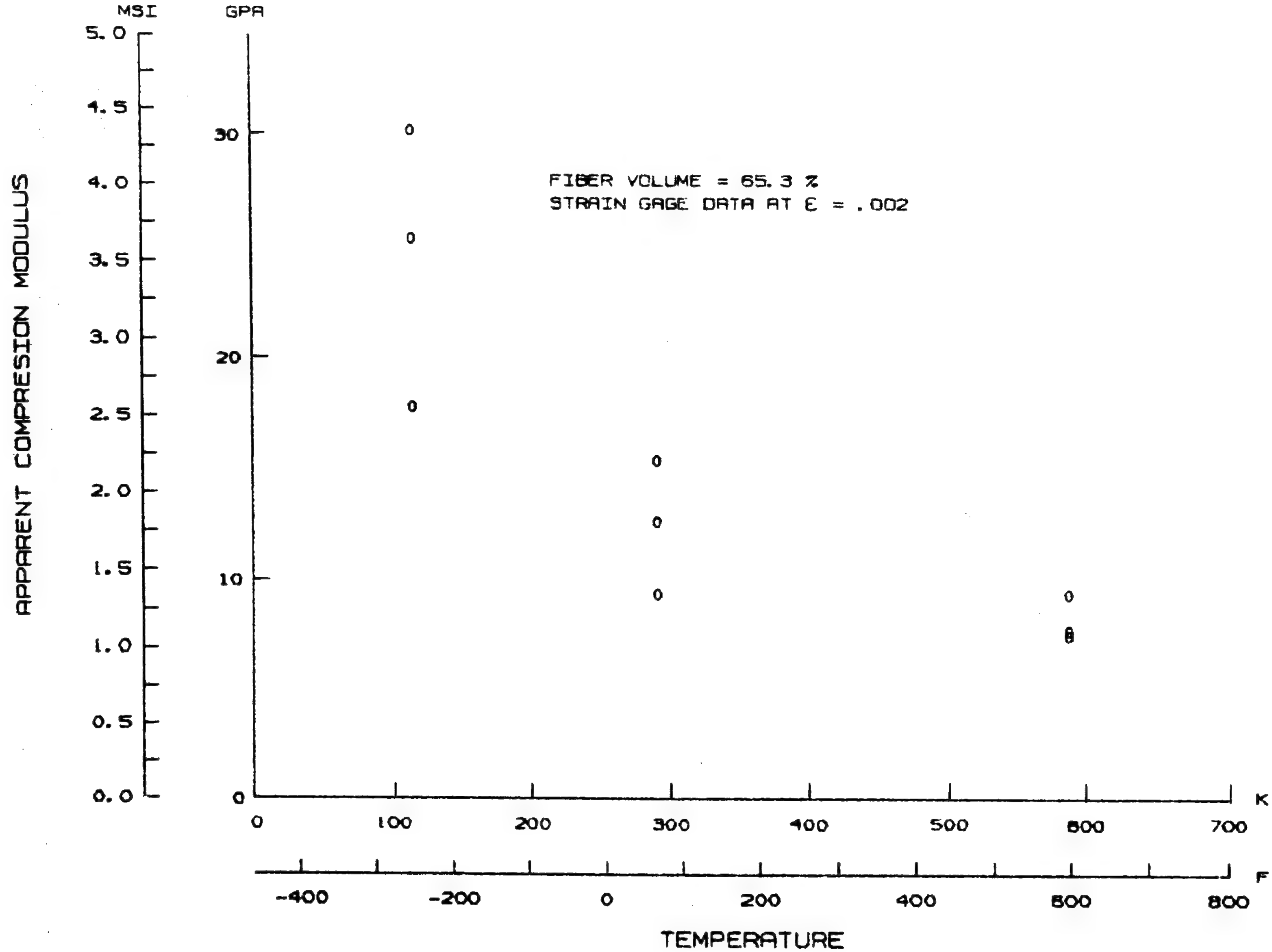


Figure 6.4-10: Celion 6000/PMR-15 Compression Tests $(\pm 45)_{4S}$ - Modulus

6.5 In-Plane Shear Tests

This section presents test procedures and test results for in-plane rail shear tests of a $(0/+45/90/-45)_S$ laminate. Shear modulus data from these tests and from tension tests* of this laminate are compared with laminate theory predictions. In addition, the in-plane shear modulus for a single lamina, G_{12}, is determined from the results of the $(\pm 45)_{2S}$ tension tests*.

6.5.1 Rail Shear Tests

6.5.1.1 Test Procedures

In-plane shear tests (test 7 of Matrix 1A) were performed using bolted rail shear fixtures provided by NASA LaRC. A typical test set up is shown in Figure 6.5-1. Specimens were loaded diagonally (Fig. 6.5-2) using a Baldwin Universal test machine. Test specimens were removed from the storage oven, bolted (61 N-m (45 ft-lb) torque) to the rail fixtures and installed in the test machine. Where applicable, strain gage output was recorded using the data aquisition system. Load versus strain was also obtained using a deflectometer outputting on an x-y recorder. Thermocouples were installed on the test specimen and on the top and bottom rails to monitor temperature gradients. Only one thermocouple was used on the room temperature specimen to assure that it had cooled to room temperature after removal from the storage oven. A cross head travel of 2.1×10^{-5} m/sec (.05 in/min) was applied and controlled using a potentiometer connected to the test machine.

* Presented in Section 6.3.

6.5.1.2 Test Results

Test results are presented in Table 6.5-1. Typical failed specimens are shown in Figure 6.5-3.

Test results are plotted as functions of temperature in Figures 6.5-4 and 6.5-5. The data show a 15% drop in laminate shear strength at elevated temperature. Laminate shear modulus is not significantly affected by temperature. The shear modulus was calculated at an engineering shear strain of 0.26%. At this shear strain level, incremental change in back-to-back strain gage output varied from 0.6% to 37% with an average of 9%. Extensometer output was based on the relative displacement of the rails. Using the relative displacement of the rails proved insatisfactory. This was shown by extensometer shear modulus results approximately 60% lower than those obtained from the strain gage output. For this reason, shear modulus data is reported only for the strain gaged specimens.

The in-plane shear modulus, G_{xy}, of the $(0/+45/90/-45)_S$ laminate was also calculated from the results of the simple tension tests of this laminate.* G_{xy} was calcualted from the tension tests by the method of Rosen and Petit (Ref. 2) as follows:

$$G_{xy} = \frac{E_x}{2(1+\nu_{xy})}$$

where E_x = modulus of $(0/+45/90/-45)_S$ laminate
ν_{xy} = Poisson's ratio of $(0/+45/90/-45)_S$ laminate

Since E_x and ν_{xy} are reported at an extensional strain of $\varepsilon = .002$, G_{xy} is reported at a corresponding engineering shear strain of $\gamma_{xy} = \varepsilon(1+\nu_{xy}) = .0026$ for $\nu_{xy} \simeq .3$.

* Presented in Section 6.3.

G_{xy} obtained from the in-plane (rail shear) tests and the tension tests are compared with laminate theory predictions for G_{xy} (based on unidirectional properties) in Table 6.5-2. The results compare very well.

6.5.2 Single Lamina In-Plane Shear Modulus (G_{12})

The lamina in-plane shear modulus in the principal fiber direction, G_{12}, was obtained from the $(\pm 45)_{2S}$ tension tests using the method of Rosen and Petit (Ref. 2) as follows:

$$G_{12} = \frac{E_x}{2(1+\nu_{xy})}$$

where E_x = modulus of $(\pm 45)_{2S}$ laminate

ν_{xy} = Poisson's ratio of $(\pm 45)_{2S}$ laminate

Since E_x and ν_{xy} are reported at an extensional strain of $\epsilon = 0.002$, the in-plane lamina shear modulus is reported at a corresponding engineering shear strain of $\gamma_{12} = \epsilon\,(1+\nu_{xy}) = 0.0036$ for $\nu_{xy} \simeq 0.8$. These results are given in Table 6.5-3 and show a drop in shear modulus, G_{12}, due to an increase in temperature. This is as expected since G_{12} is a matrix dominated property.

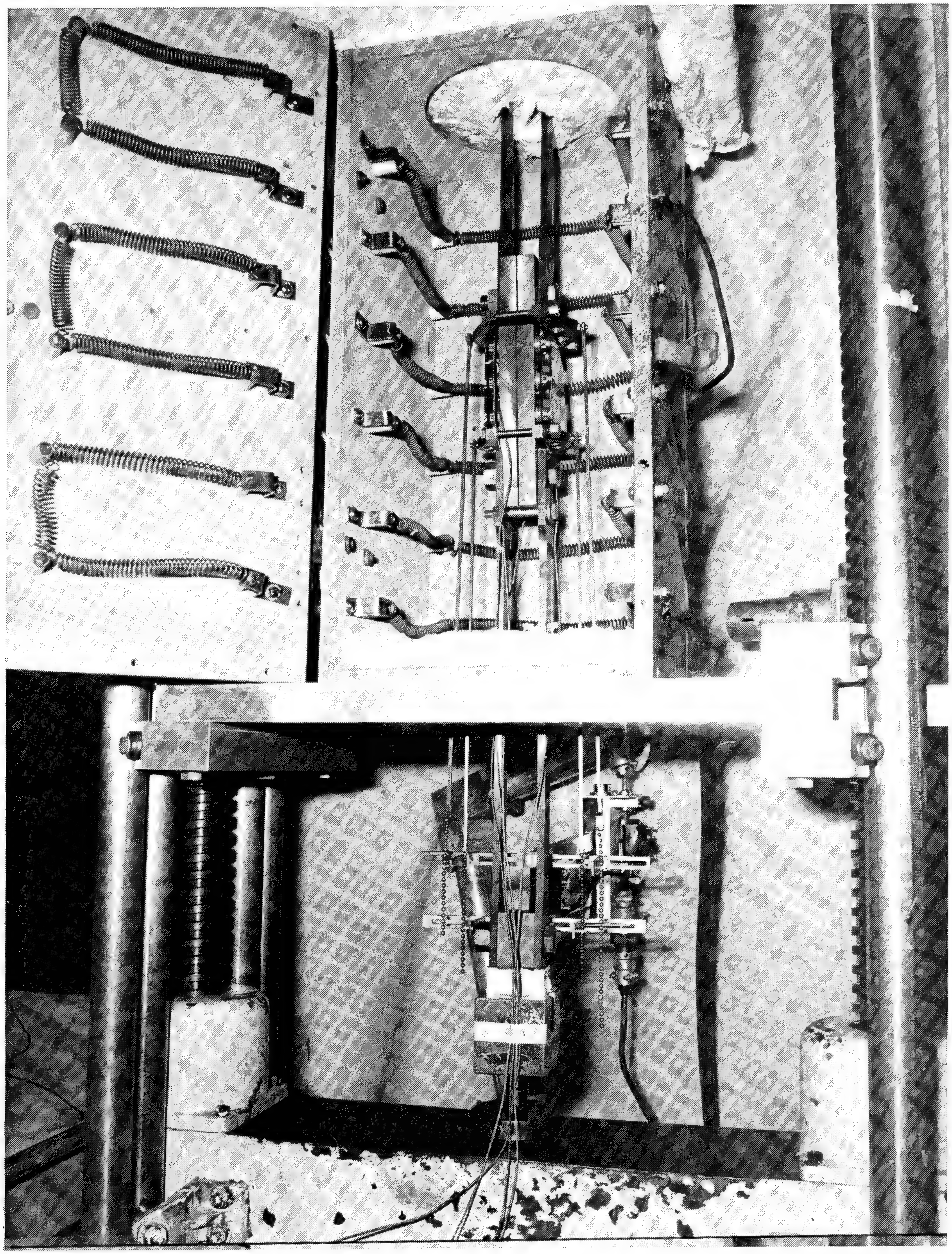


Figure 6.5-1: Celion 6000/PMR-15 Design Allowables Inplane Shear Test Setup

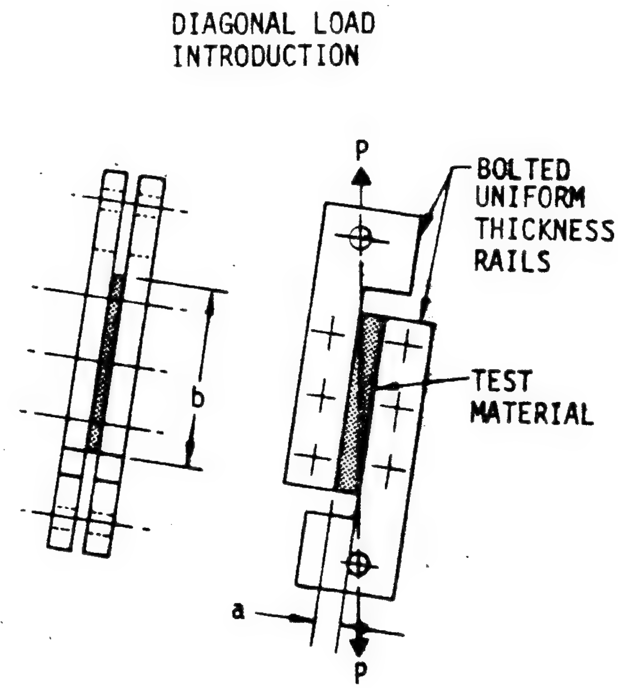


Figure 6.5-2: In-Plane Shear Tests Diagonal Load Introduction

TABLE 6.5-1. CELION 6000/PMR-15 DESIGN ALLOWABLES INPLANE SHEAR TESTS [0/+45/90/-45]S LAYUP

(a) SI UNITS

SPECIMEN	THICKNESS MM	LENGTH MM	DISTANCE BETWEEEN RAILS MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA	LAMINATE SHEAR MODULUS γ_{XY}=.0026 GPA
1A-7-1	1.12	76.784	7.87	116.	28357.	330.	
1A-7-2	1.07	76.893	7.95	116.	25844.	315.	
1A-7-3	1.10	76.827	7.92	116.	34318.	405.	
1A-7-4	1.11	76.810	7.95	116.	32628.	383.	
1A-7-5	1.13	76.797	7.87	116.	32583.	375.	
1A-7-6	1.10	76.817	8.08	116.	33362.	394.	
1A-7-7	1.12	76.805	7.75	116.	27579.	321.	
1A-7-8	1.09	76.774	7.82	116.	27601.	331.	18.2
1A-7-9	1.06	76.784	7.98	116.	31049.	383.	16.8
1A-7-10	1.07	76.810	7.80	116.	33495.	406.	18.9
1A-7-11	1.11	76.820	7.95	294.	28202.	332.	
1A-7-12	1.09	76.820	7.72	294.	32339.	385.	
1A-7-13	1.08	76.777	7.67	294.	30871.	371.	
1A-7-14	1.10	76.810	7.77	294.	32072.	380.	
1A-7-15	1.11	76.764	8.00	294.	29759.	350.	
1A-7-16	1.12	76.797	7.42	294.	33161.	386.	
1A-7-17	1.10	76.789	7.44	294.	31783.	376.	
1A-7-18	1.10	76.797	7.44	294.	30871.	365.	17.0
1A-7-19	1.08	76.784	7.54	294.	24821.	300.	17.7
1A-7-20	1.04	76.792	7.80	294.	26289.	330.	17.1
1A-7-21	1.08	76.810	7.62	589.	26578.	320.	
1A-7-22	1.12	76.784	7.70	589.	26912.	314.	
1A-7-23	1.08	76.766	7.67	589.	24932.	301.	
1A-7-24	1.10	76.835	7.49	589.	27379.	323.	
1A-7-25	1.07	76.817	7.90	589.	26489.	321.	
1A-7-26	1.11	76.784	8.05	589.	25533.	299.	
1A-7-27	1.09	76.810	7.92	589.	25800.	308.	
1A-7-28	1.10	76.807	8.15	589.	25511.	303.	19.2
1A-7-29	1.11	76.799	8.08	589.	23976.	281.	18.2
1A-7-30	1.11	76.759	7.65	589.	25310.	298.	17.6*

* 1 STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.5-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	LENGTH IN	DISTANCE BETWEEN RAILS IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI	LAMINATE SHEAR MODULUS γ_{XY}=.0026 MSI
1A-7-1	.0441	3.0230	.310	-250.	6375.	47.8	
1A-7-2	.0420	3.0273	.313	-250.	5810.	45.7	
1A-7-3	.0434	3.0247	.312	-250.	7715.	58.8	
1A-7-4	.0436	3.0240	.313	-250.	7335.	55.6	
1A-7-5	.0445	3.0235	.310	-250.	7325.	54.4	
1A-7-6	.0434	3.0243	.318	-250.	7500.	57.1	
1A-7-7	.0441	3.0238	.305	-250.	6200.	46.5	
1A-7-8	.0428	3.0226	.308	-250.	6205.	48.0	2.64
1A-7-9	.0416	3.0230	.314	-250.	6980.	55.5	2.44
1A-7-10	.0423	3.0240	.307	-250.	7530.	58.9	2.74
1A-7-11	.0436	3.0244	.313	70.	6340.	48.1	
1A-7-12	.0431	3.0244	.304	70.	7270.	55.8	
1A-7-13	.0427	3.0227	.302	70.	6940.	53.8	
1A-7-14	.0433	3.0240	.306	70.	7210.	55.1	
1A-7-15	.0436	3.0222	.315	70.	6690.	50.8	
1A-7-16	.0440	3.0235	.292	70.	7455.	56.0	
1A-7-17	.0434	3.0232	.293	70.	7145.	54.5	
1A-7-18	.0434	3.0235	.293	70.	6940.	52.9	2.46
1A-7-19	.0424	3.0230	.297	70.	5580.	43.5	2.57
1A-7-20	.0409	3.0233	.307	70.	5910.	47.8	2.48
1A-7-21	.0426	3.0240	.300	600.	5975.	46.4	
1A-7-22	.0439	3.0230	.303	600.	6050.	45.6	
1A-7-23	.0424	3.0223	.302	600.	5605.	43.7	
1A-7-24	.0435	3.0250	.295	600.	6155.	46.8	
1A-7-25	.0423	3.0243	.311	600.	5955.	46.5	
1A-7-26	.0438	3.0230	.317	600.	5740.	43.4	
1A-7-27	.0429	3.0240	.312	600.	5800.	44.7	
1A-7-28	.0432	3.0239	.321	600.	5735.	43.9	2.78
1A-7-29	.0438	3.0236	.318	600.	5390.	40.7	2.64
1A-7-30	.0436	3.0220	.301	600.	5690.	43.2	2.55*

* 1 STRAIN GAGE FAULTY

NOTE: FIBER VOLUME = 65.3 %

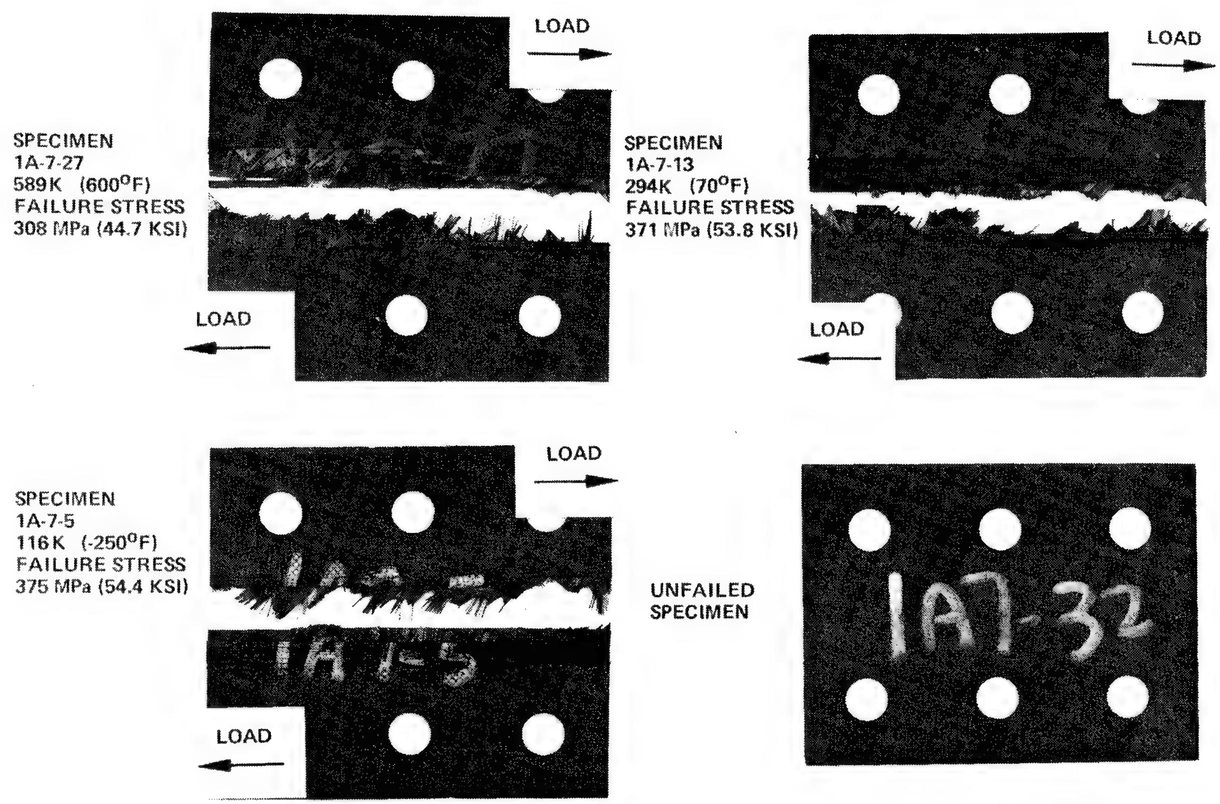
Table 6.5-2: Celion 6000/PMR-15 Design Allowables in-Plane Shear Modulus G_{xy} of $[0/+45/90/-45]_S$ Laminate

TEMPERATURE		AVERAGE LAMINATE TANGENT SHEAR MODULUS G_{xy}* BASED ON RAIL SHEAR TESTS		AVERAGE LAMINATE TANGENT SHEAR MODULUS G_{xy}* BASED ON TENSION TEST		LAMINATE SHEAR MODULUS G_{xy} BASED ON UNIDIRECTIONAL PROPERTIES AND LAMINATE PLATE THEORY	
K	(°F)	GPa	(10^6 psi)	GPa	(10^6 psi)	GPa	(10^6 psi)
116	(-250)	18.0	(2.61)	19.2	(2.79)	20.5	(2.98)
294	(70)	17.2	(2.50)	18.8	(2.72)	19.4	(2.82)
589	(600)	18.3	(2.66)	18.4	(2.67)	18.5	(2.69)

* Based on 3 specimens for each temperature. Tangent modulus reported at an engineering shear strain level of γ_{xy} = .0026.

Table 6.5-3: Celion 6000/PMR-15 Design Allowable Lamina In-Plane Shear Modulus G_{12}

TEST TYPE	LAYUP	SPECIMEN	TEST TEMP K (°F)	TANGENT MODULUS ε = .002 E_x GPa (10^6 psi)	POISSON'S RATIO ε = .002 ν_{xy}	LAMINA SHEAR MODULUS G_{12} γ_{12}=.0036 GPa (10^6 psi)
TENSION	$[\pm45]_{2S}$	1A-3-8	116 (-250)	21.0 (3.04)	.778	5.88 (.853)
	$[\pm45]_{2S}$	1A-3-9	116 (-250)	22.0 (3.19)	.752	6.28 (.911)
	$[\pm45]_{2S}$	1A-3-10	116 (-250)	19.2 (2.78)	.687	5.67 (.823)
TENSION	$[\pm45]_{2S}$	1A-3-18	294 (70)	17.6 (2.55)	.850	4.74 (.688)
	$[\pm45]_{2S}$	1A-3-19	294 (70)	16.8 (2.43)	.903	4.41 (.640)
	$[\pm45]_{2S}$	1A-3-20	294 (70)	17.9 (2.59)	.867	4.78 (.694)
TENSION	$[\pm45]_{2S}$	1A-3-28	589 (600)	8.83 (1.28)	.842	2.40 (.348)
	$[\pm45]_{2S}$	1A-3-29	589 (600)	8.48 (1.28)	.835	2.32 (.336)
	$[\pm45]_{2S}$	1A-3-30	589 (600)	8.00 (1.16)	.801	2.21 (.321)



Celion 6000/PMR-15 Design Allowables
In-Plane Shear Tests $[0/+45/90/-45]_S$ Layup

Figure 6.5-3: Celion 6000/PMR-15 In-Plane Shear Tests $[0/+45/90/-45]_S$ Layup - Failed Specimens

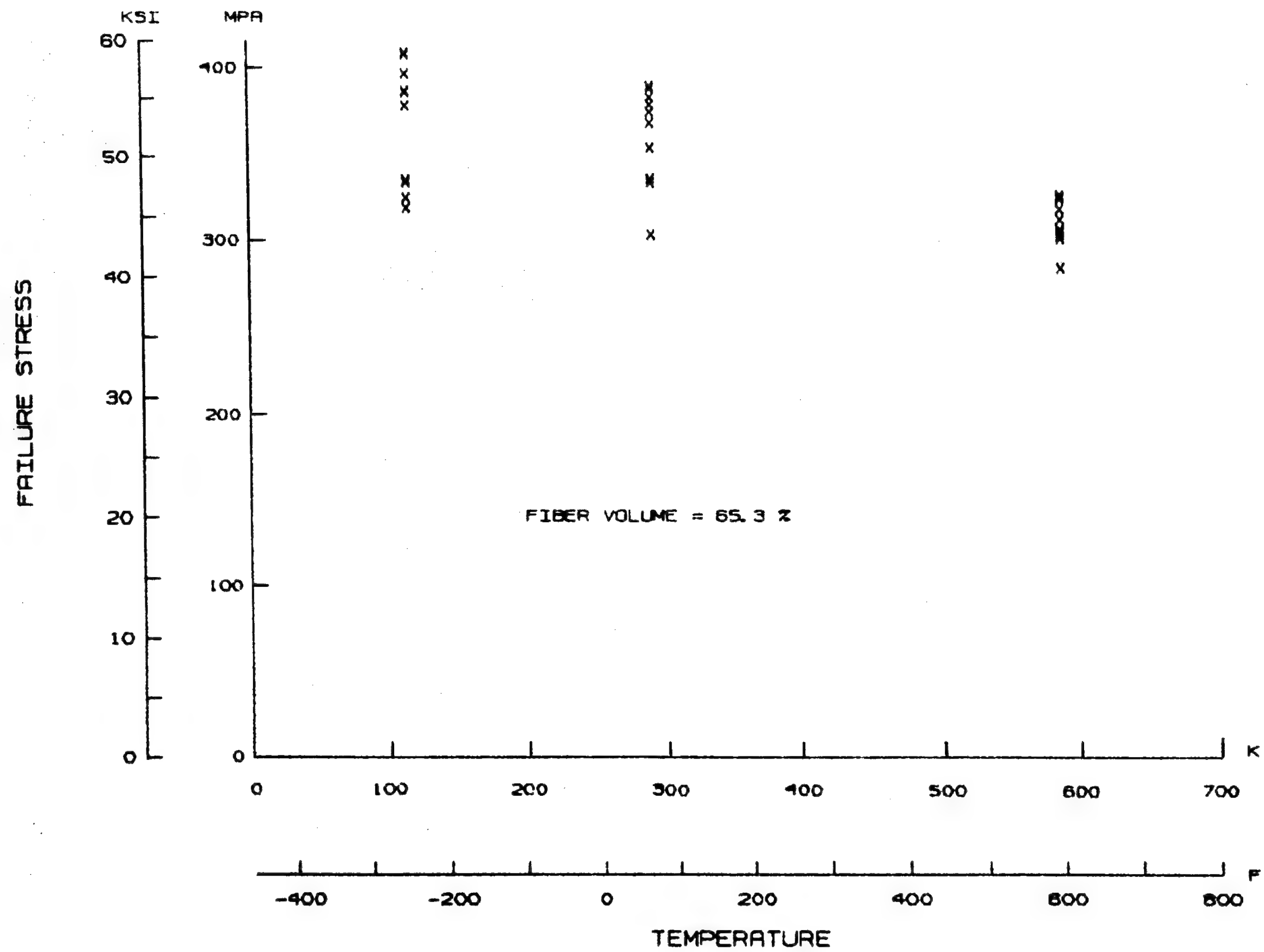


Figure 6.5-4: Celion 6000/PMR-15 In-Plane Shear Tests $(0/+45/90/-45)_S$ - Failure Stress

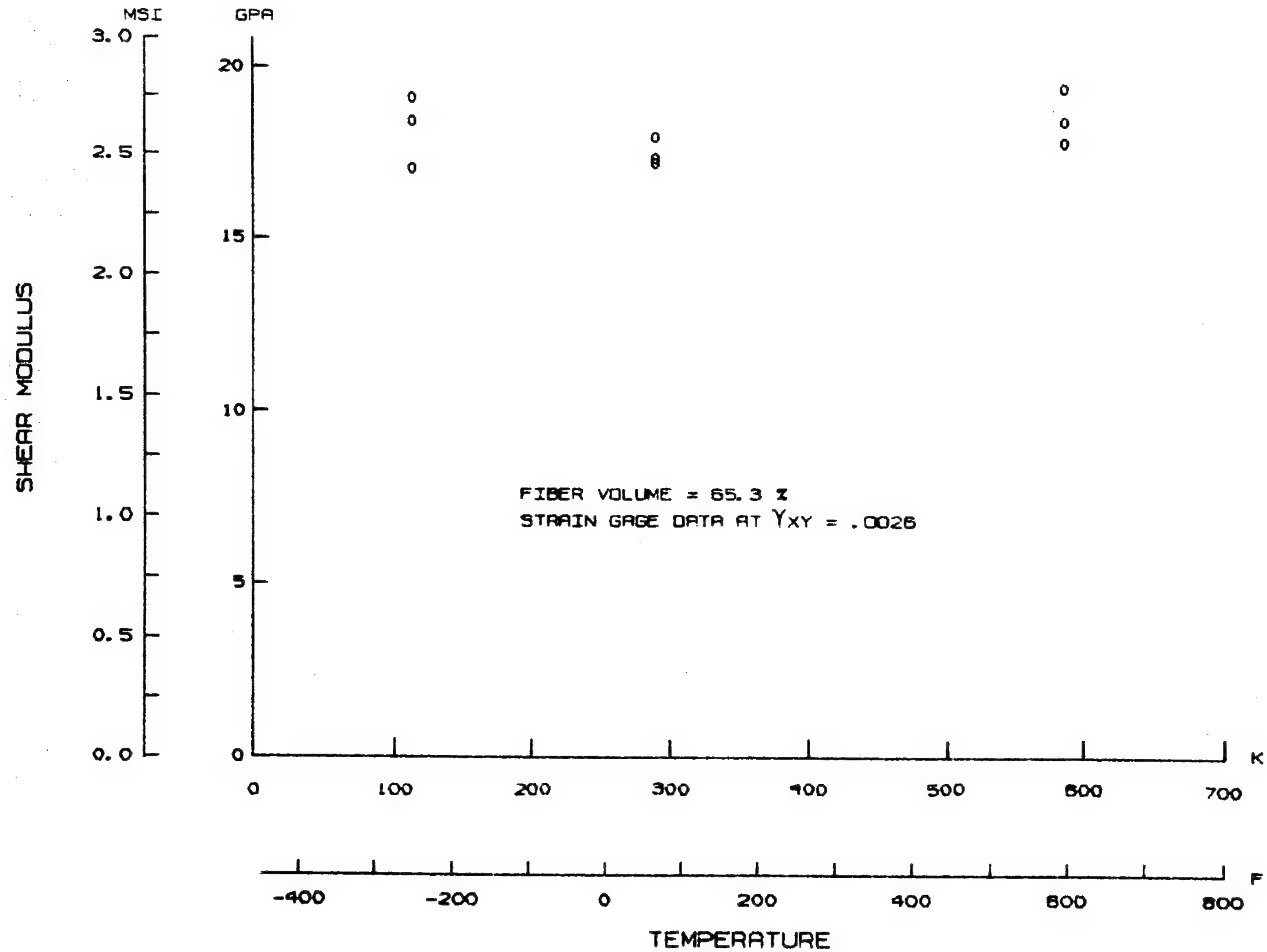


Figure 6.5-5: Celion 6000/PMR-15 In-Plane Shear Tests $(0/+45/90/-45)_S$ - Shear Modulus

6.6 Interlaminar (Short Beam) Shear Tests

This section presents test procedures and test results of interlaminar (short beam) shear tests of a $(0)_{20}$ laminate.

6.6.1 Test Procedures

Interlaminar (short beam) shear tests (test 8 of Matrix 1A) were conducted in accordance with ASTM D2344. Specimens were loaded in a 3 point bend fixture using a Baldwin Universal test machine. A typical test set up is shown in Figure 6.6-1. The test fixture has an adjustable span and uses 1.59mm (1/16 inch) radius reaction points and a 3.18mm (1/8 inch) radius load point. Specimens were removed from the storage oven and installed in the test fixture. A thermocouple was attached to the specimen. Specimens were loaded to failure using a cross head travel of 2.1×10^{-5} m/sec (.05 in/min).

6.6.2 Test Results

Test results are shown in Table 6.6-1. Typical failed specimens are shown in Figure 6.6-2.

Failure stress is plotted as a function of temperature in Figure 6.6-3. The data indicate that interlaminar shear strength decreases with increasing temperature, over the temperature range of 116K (-250^{o}F) to 589K (600^{o}F). This decrease is 16% going from 116K (-250^{o}F) to 294K (70^{o}F) and 49% going from 294K (70^{o}F) to 589K (600^{o}F). This demonstrates the important role that the matrix plays in providing interlaminar shear strength.

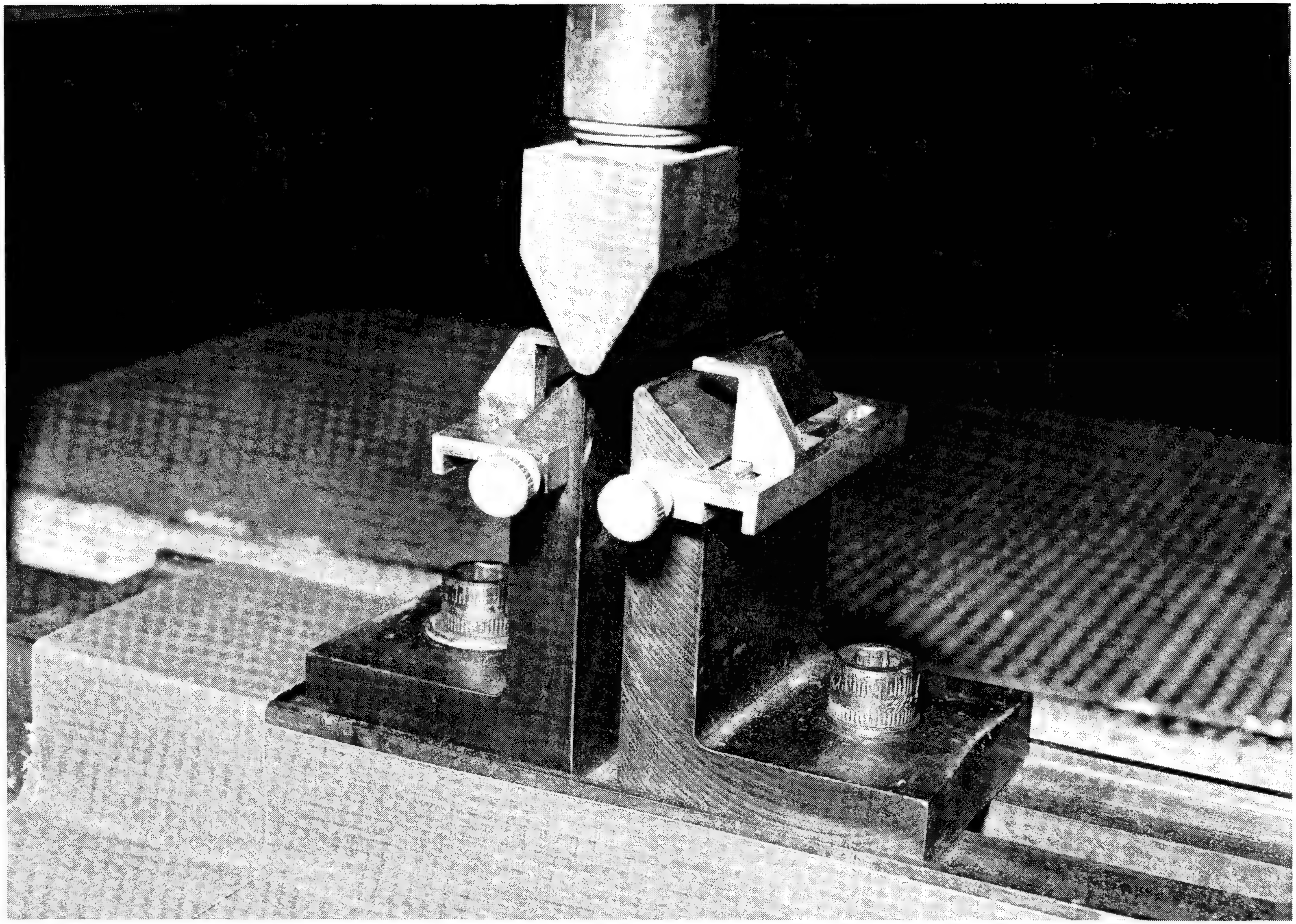


Figure 6.6-1: Interlaminar Shear Test Setup Celion 6000/PMR-15 Design Allowables

TABLE 6.6-1. CELION 6000/PMR-15 DESIGN ALLOWABLES INTERLAMINAR SHEAR TESTS [0]20 LAYUP

(a) SI UNITS

SPECIMEN	THICKNESS MM	WIDTH MM	DISTANCE BETWEEN SUPPORTS MM	TEST TEMPERATURE K	FAILURE LOAD N	FAILURE STRESS MPA
1A-8-19	2.868	6.320	11.	116.	2949.	122.0
1A-8-20	2.662	6.289	11.	116.	2647.	118.6
1A-8-21	3.025	6.368	11.	116.	3194.	124.1
1A-8-22	2.794	6.330	11.	116.	3047.	128.9
1A-8-24	2.619	6.375	11.	116.	2914.	131.0
1A-8-10	2.794	6.307	11.	294.	2647.	112.4
1A-8-11	2.733	6.375	11.	294.	2513.	108.2
1A-8-12	2.799	6.317	11.	294.	2349.	99.3
1A-8-13	2.603	6.309	11.	294.	2229.	102.0
1A-8-14	2.558	6.284	11.	294.	2295.	106.9
1A-8-15	2.791	6.388	11.	294.	2349.	98.6
1A-8-16	2.573	6.373	11.	294.	2291.	104.8
1A-8-17	2.652	6.358	11.	294.	2455.	108.9
1A-8-18	2.639	6.355	11.	294.	2331.	104.1
1A-8-2	2.784	6.355	11.	589.	1308.	55.2
1A-8-3	2.880	6.375	11.	589.	1272.	51.7
1A-8-4	2.736	6.380	11.	589.	1228.	52.7
1A-8-5	2.809	6.360	11.	589.	1277.	53.4
1A-8-6	2.565	6.363	11.	589.	1174.	53.8

NOTE: FIBER VOLUME = 65.3 %

TABLE 6.6-1. CONCLUDED

(b) U.S. CUSTOMARY UNITS

SPECIMEN	THICKNESS IN	WIDTH IN	DISTANCE BETWEEN SUPPORTS IN	TEST TEMPERATURE F	FAILURE LOAD LBS	FAILURE STRESS KSI
1A-8-19	.1129	.2488	.44	-250.	663.	17.7
1A-8-20	.1048	.2476	.44	-250.	595.	17.2
1A-8-21	.1191	.2507	.44	-250.	718.	18.0
1A-8-22	.1100	.2492	.44	-250.	685.	18.7
1A-8-24	.1031	.2510	.44	-250.	655.	19.0
1A-8-10	.1100	.2483	.44	70.	595.	16.3
1A-8-11	.1076	.2510	.44	70.	565.	15.7
1A-8-12	.1102	.2487	.44	70.	528.	14.4
1A-8-13	.1025	.2484	.44	70.	501.	14.8
1A-8-14	.1007	.2474	.44	70.	516.	15.5
1A-8-15	.1099	.2515	.44	70.	528.	14.3
1A-8-16	.1013	.2509	.44	70.	515.	15.2
1A-8-17	.1044	.2503	.44	70.	552.	15.8
1A-8-18	.1039	.2502	.44	70.	524.	15.1
1A-8-2	.1096	.2502	.44	600.	294.	8.0
1A-8-3	.1134	.2510	.44	600.	286.	7.5
1A-8-4	.1077	.2512	.44	600.	276.	7.7
1A-8-5	.1106	.2504	.44	600.	287.	7.8
1A-8-6	.1010	.2505	.44	600.	264.	7.8

NOTE: FIBER VOLUME = 65.3 %

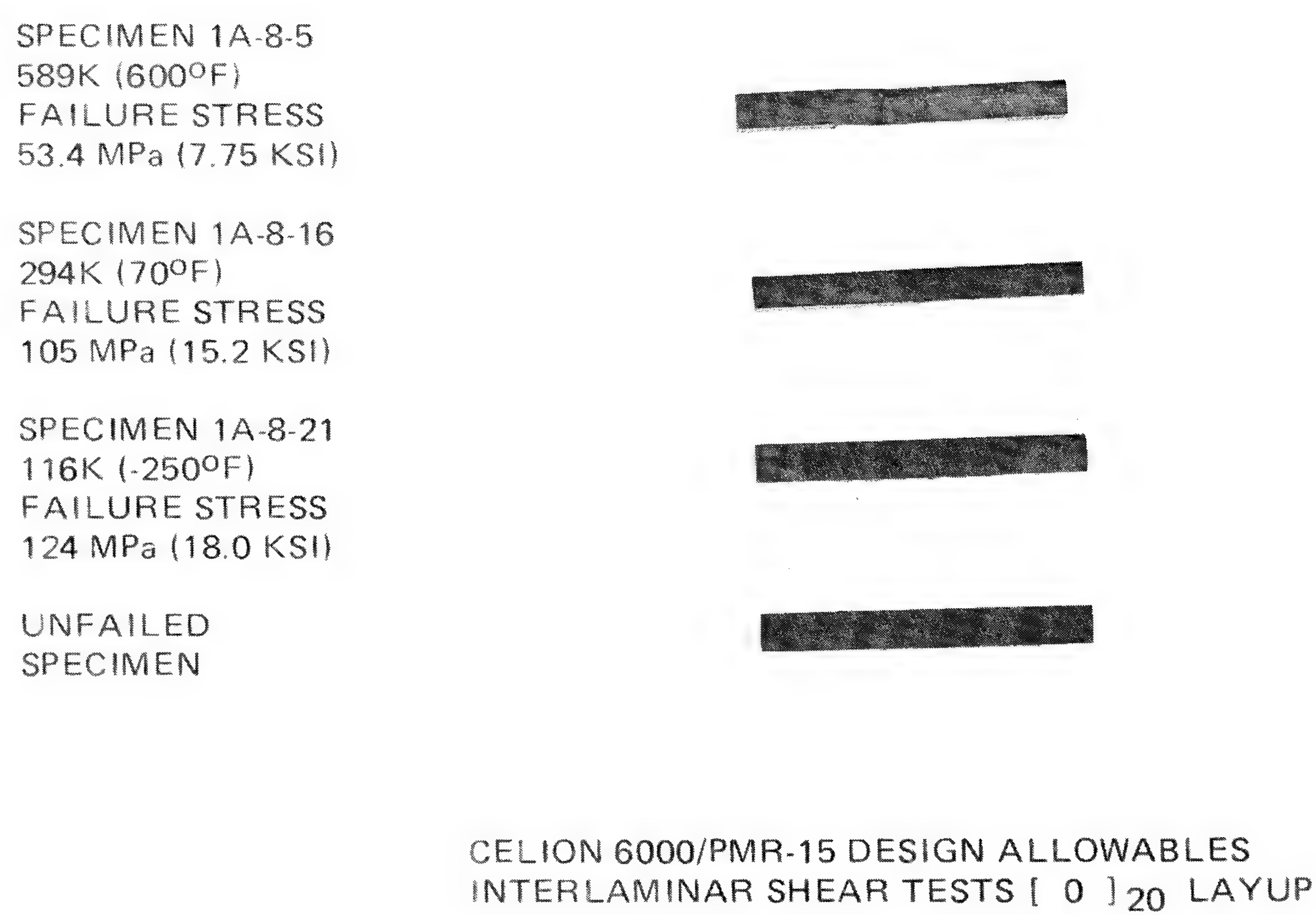


Figure 6.6-2: Celion 6000/PMR-15 Design Allowables Interlaminar Shear Tests $[0]_{20}$ Layup - Failed Specimens

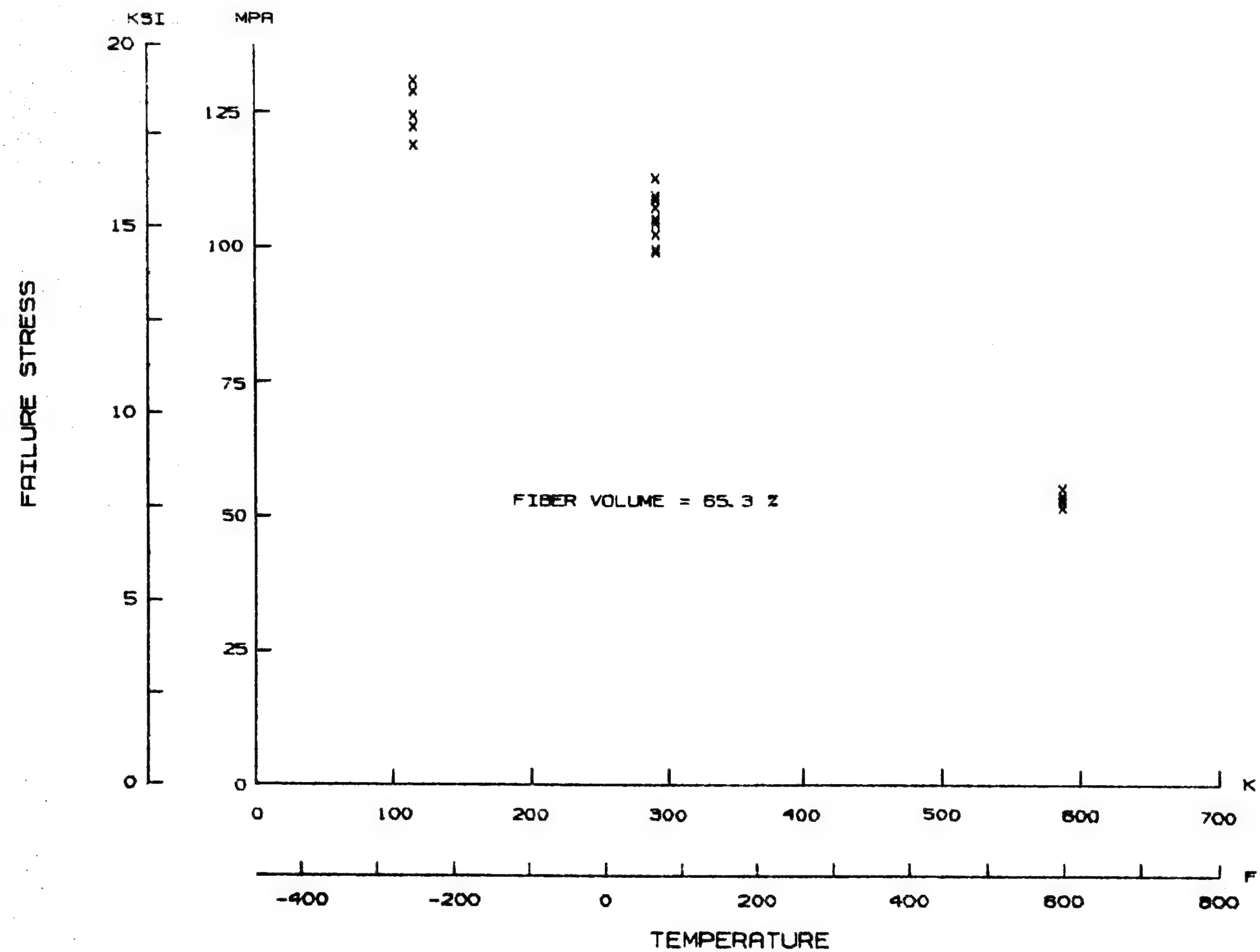


Figure 6.6-3: Celion 6000/PMR-15 Interlaminar Shear Tests $(0)_{20}$ Layup - Failure Stress

6.7 Data Summary

A summary of all Celion 6000/PMR-15 test results is given in Table 6.7-1. Data shown are test type, laminate lay-up, temperature, number of specimens, average test results and coefficient of variation. Test results are very consistent as shown by the small coefficients of variation and may be used for preliminary sizing of graphite/polymide structure.

Table 6.7-1: Celion 6000/PMR-15 Design Allowables Summary
Baseline "Dry" 65.3% Fiber Volume

TEST TYPE	LAMINATE LAYUP	TEMPERATURE K (°F)	NUMBER OF SPECIMENS	AVERAGE FAILURE STRESS MPa (ksi)	▷1	EXTENSOMETER DATA: AVERAGE MODULUS Ex GPa (10^6 psi)	▷1	EXTENSOMETER DATA: AVERAGE FAILURE STRAIN ult	▷1	STRAIN GAGE DATA: AVG. TANGENT MODULUS ϵ = .002 E_x* GPa (10^6 psi)	STRAIN GAGE DATA: AVERAGE POISSON'S RATIO ϵ = .002 ν_{xy}*	STRAIN GAGE DATA: AVERAGE LAMINA SHEAR MODULUS γ_{12} = .0036 G_{12}* GPa (10^6 psi)	STRAIN GAGE DATA: AVERAGE LAMINATE SHEAR MODULUS γ_{xy} = .0026 G_{xy}* GPa (10^6 psi)
TENSION	$[0]_8$	116 (-250)	10	1590 (231)	.052	135 (19.6)	.053	.0113●	.085	134++ (19.5)	.383++	—	—
		294 (70)	10	1510 (219)	.099	132 (19.1)	.037	.0112●	.076	136 (19.7)	.333	—	—
		589 (600)	10	1600 (232)	.030	135 (19.6)	.071	.0124●	.079	143 (20.8)	.316	—	—
TENSION	$[0/+45/90/-45]_S$	116 (-250)	10	529 (76.7)	.054	44.8 (6.5)	.044	.0119	.087	50.7++ (7.35)	.317++	—	19.2++ (2.79)
		294 (70)	10	525 (76.1)	.116	48.3 (7.0)	.047	.0118	.124	50.3 (7.29)	.340	—	18.8 (2.72)
		589 (600)	10	516 (74.8)	.045	46.2 (6.7)	.021	.0119	.054	49.7+ (7.21)	.349+	—	18.4+ (2.67)
TENSION	$[\pm 45]_{2S}$	116 (-250)	10	131 (19.0)	.023	20.0 (2.9)	.073	.0128●	.177	20.7 (3.00)	.739	5.94 (.862)	—
		294 (70)	10	123 (17.9)	.017	17.9 (2.6)	.065	.0129	.119	17.4 (2.52)	.873	4.65 (.674)	—
		589 (600)	11	108 (15.6)	.069	11.7 (1.7)	.093	.0795	.162	8.41 (1.22)	.826	2.31 (.335)	—
COMPRESSION	$[0]_{16}$	116 (-250)	10	1250 (182)	.098	—	—	—	—	132**+ (19.1)	.376**+	—	—
		294 (70)	10	972 (141)	.163	—	—	—	—	122** (17.7)	.331**	—	—
		589 (600)	10	549 (79.6)	.106	—	—	—	—	119***+++ (17.3)	.301***+++	—	—
COMPRESSION	$[0/+45/90/-45]_{2S}$	116 (-250)	10	614 (89.1)	.162	—	—	—	—	60.5 (8.78)	.354	—	22.4 (3.25)
		294 (70)	10	545 (79.0)	.060	—	—	—	—	41.9 (6.07)	.319	—	15.9 (2.30)
		589 (600)	10	380 (55.1)	.049	—	—	—	—	50.7** (7.35)	.381**	—	18.3** (2.66)
COMPRESSION	$[\pm 45]_{4S}$	116 (-250)	10	231 (33.5)	.266	—	—	—	—	24.3+++ (3.52)	.664+++	7.31+++ (1.06)	—
		294 (70)	10	168 (24.4)	.081	—	—	—	—	12.3+ (1.79)	.654+	3.70+ (.537)	—
		589 (600)	10	101 (14.6)	.165	—	—	—	—	8.14 (1.18)	.833	2.22 (.322)	—
INPLANE SHEAR	$[0/+45/90/-45]_S$	116 (-250)	10	364 (52.8)	.099	—	—	—	—	—	—	—	18.0 (2.61)
		294 (70)	10	357 (51.8)	.080	—	—	—	—	—	—	—	17.2 (2.50)
		589 (600)	10	307 (44.5)	.043	—	—	—	—	—	—	—	18.3++++ (2.66)
INTERLAMINAR SHEAR	$[0]_{20}$	116 (-250)	5	125 (18.1)	.040	—	—	—	—	—	—	—	—
		294 (70)	9	105 (15.2)	.044	—	—	—	—	—	—	—	—
		589 (600)	5	53.4 (7.7)	.024	—	—	—	—	—	—	—	—

▷1 Coefficient of variation (standard deviation/average).
* 3 specimens unless noted.
** 2 specimens.
*** 1 specimen.
\+ 1 longitudinal strain gage faulty on 1 specimen.
\++ 1 transverse strain gage faulty on 1 specimen.
\+++ 1 longitudinal and 1 transverse strain gage faulty on 1 specimen.
\++++ 1 strain gage faulty on 1 specimen
● 9 specimens

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7.0 COMPARISON OF CELION 3000/PMR-15 AND CELION 6000/PMR-15 DESIGN ALLOWABLES

This section presents comparisons of Celion 3000/PMR-15 and Celion 6000/PMR-15 laminates with lay-ups of $(0)_N$ $(\pm 45)_{NS}$, and $(0/\pm 45/90)^*_{NS}$. In order to make a meaningful comparison, the data were normalized to 58% fiber volume using a rule of mixtures-mechanics of materials approach. Based on heuristic arguments, laminate strengths were normalized in the same manner as laminate stiffness. Normalizing factors used for Celion 3000/PMR-15 and Celion 6000/PMR- 15 are given in Tables 7.0-1 and 7.0-2 respectively.

7.1 Comparison of 0_N Laminates

A comparison of Celion 3000 and Celion 6000 $(0)_N$ laminates is given in Figure 7.1-1. There is no significant difference in the unidirectional tensile strength of the two for the temperatures tested. The Celion 6000 based laminates, however, have 15% less unidirectional tensile modulus.

7.2 Comparison of $(0/\pm 45/90)^*_{NS}$ Laminates

A comparison of strength and modulus of Celion 3000 and Celion 6000 $(0/\pm 45/90)^*_{NS}$ laminates is shown in Figures 7.2-1 and 7.2-2 respectively. Data show that the Celion 6000 laminates have approximately 20% less tension strength and modulus at room and elevated temperature. It is difficult to draw conclusions from the compression data since the Celion 3000 laminates were tested in an end loaded fixture and the Celion 6000 laminates were tested in an IITRI** fixture. In addition, the differences in

*Stacking order varies.

**IITRI: Illinois Institute of Technology Research Institute

lay-up stacking could have a more pronounced affect on the compression strengths than on tension. Compression data are shown for completeness and to allow the reader to make his own conclusions.

7.3 Comparison of $(\pm 45)_{NS}$ Laminates

A comparison of Celion 3000 and Celion 6000 $(\pm 45)_{NS}$ laminates is given in Figure 7.3-1. Data show that at room temperature the Celion 6000 laminates had 56% less tension strength and 11% less tension modulus than the Celion 3000 laminates. At elevated temperatures the Celion 6000 had 27% less tension strength and approximately the same tension modulus as the Celion 3000 laminates. Visual inspection of the failed room temperature specimens revealed extensive fiber breakage in the Celion 3000 laminates and relatively little fiber breakage in the Celion 6000 laminates. Scanning electron microscope (SEM) photographs of the failed surfaces of these specimens were inconclusive in explaining these differences. It may be that edge effects in the Celion 6000 based laminates were more severe since the plies were twice as thick. More probable is a macro-mechanical interlocking of plies in the Celion 3000 laminates which have twice as many plies as those in the Celion 6000 laminates. At elevated temperatures the strength and modulus disparity is greatly reduced. This may be explained because of the matrix dominated behavior at elevated temperature.

Table 7.0-1: Celion 3000/PMR-15 Design Allowables Factors for Normalizing From 51.4% to 58% Fiber Volume

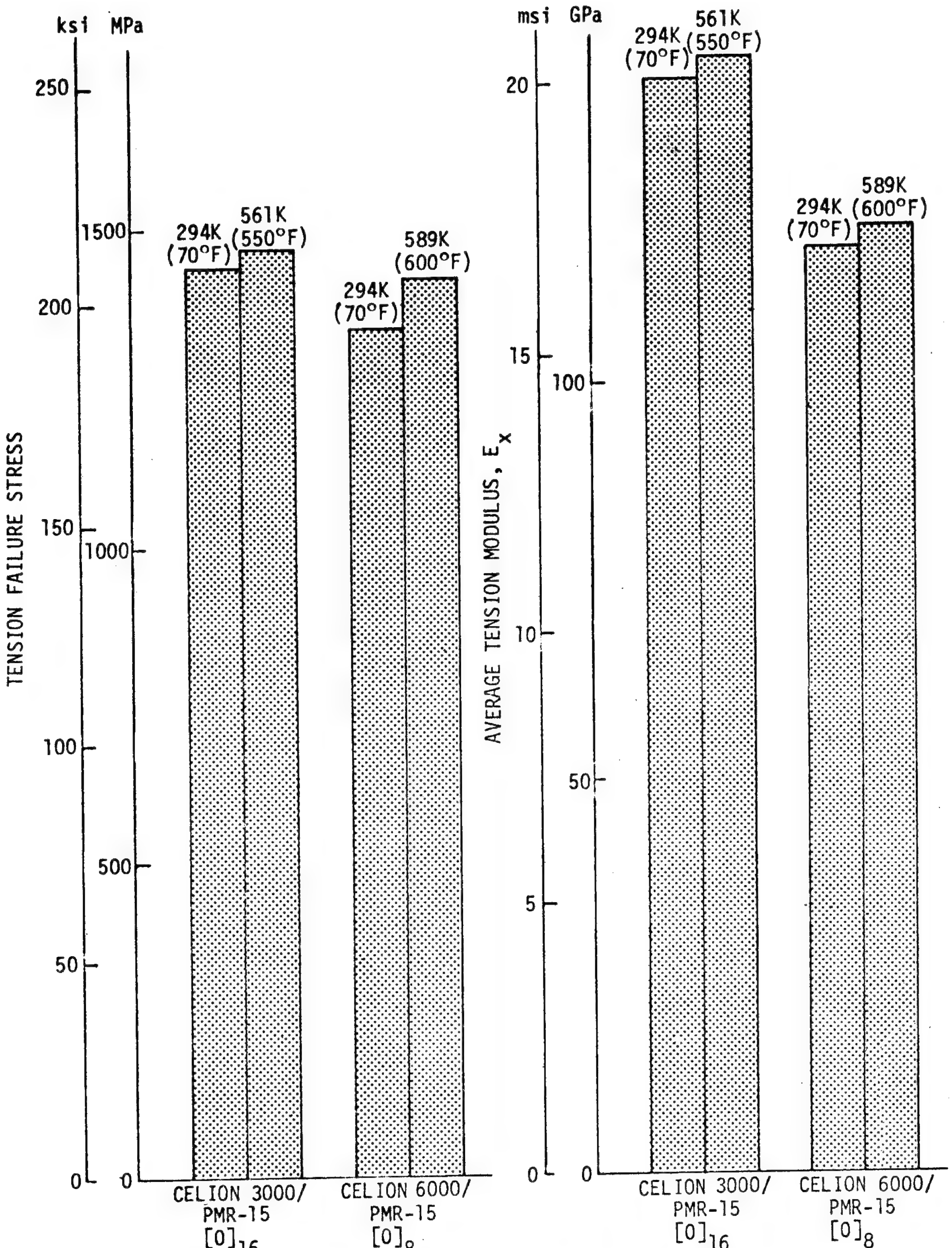
LAMINATE	NORMALIZING FACTOR	
	294K (70°F)	561K (550°F)
0°_{16}	1.128	1.128
90°_{30}	1.157	1.157
$(0/\pm45/90)_{4S}$	1.13	1.128
$(90,\pm45,0)_{4S}$	1.13	1.128
$\pm45^\circ_{8S}$	1.153	1.152
G_{12}	1.157	1.157
ν_{12}	1.0	1.0

$$\text{Property}_{58\%} = \text{Property}_{51.4\%} \times (\text{Normalizing Factor})$$

Table 7.0-2: Celion 6000/PMR-15 Design Allowables Factors for Normalizing From 65.3% F.V. to 58% F.V.

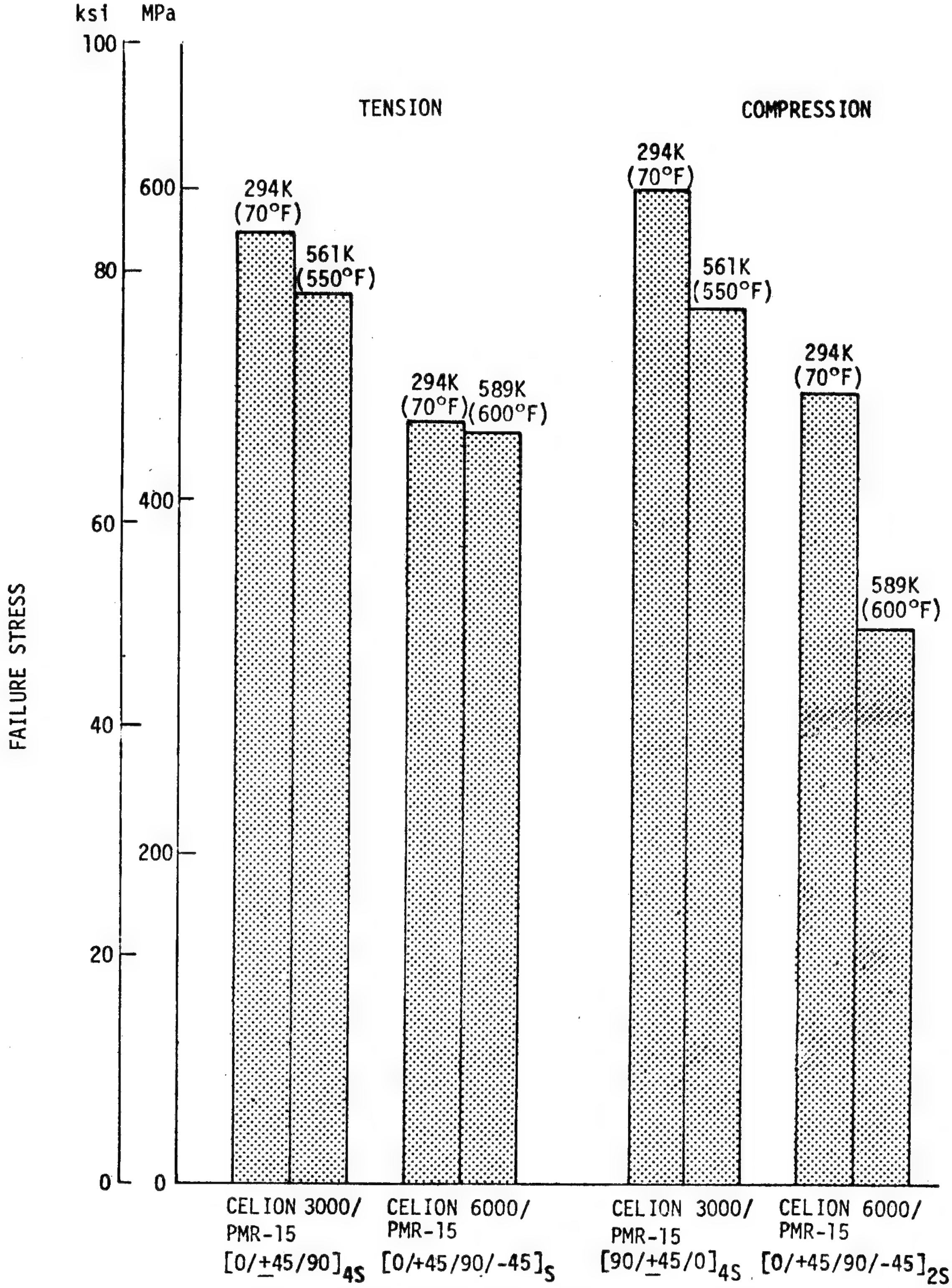
LAMINATE	NORMALIZING FACTOR	
	294K (70°F)	589K (600°F)
$[0]_8$	.888	.888
$[0/45/90/-45]_{NS}$	.881	.882
$[+45]_{NS}$	.832	.830
$[90]_N$	.826	.826
G_{12}	.826	.826
ν_{12}	1.0	1.0

$$\text{Property}_{58\%} = \text{Property}_{65.3\%} \times (\text{Normalizing Factor})$$



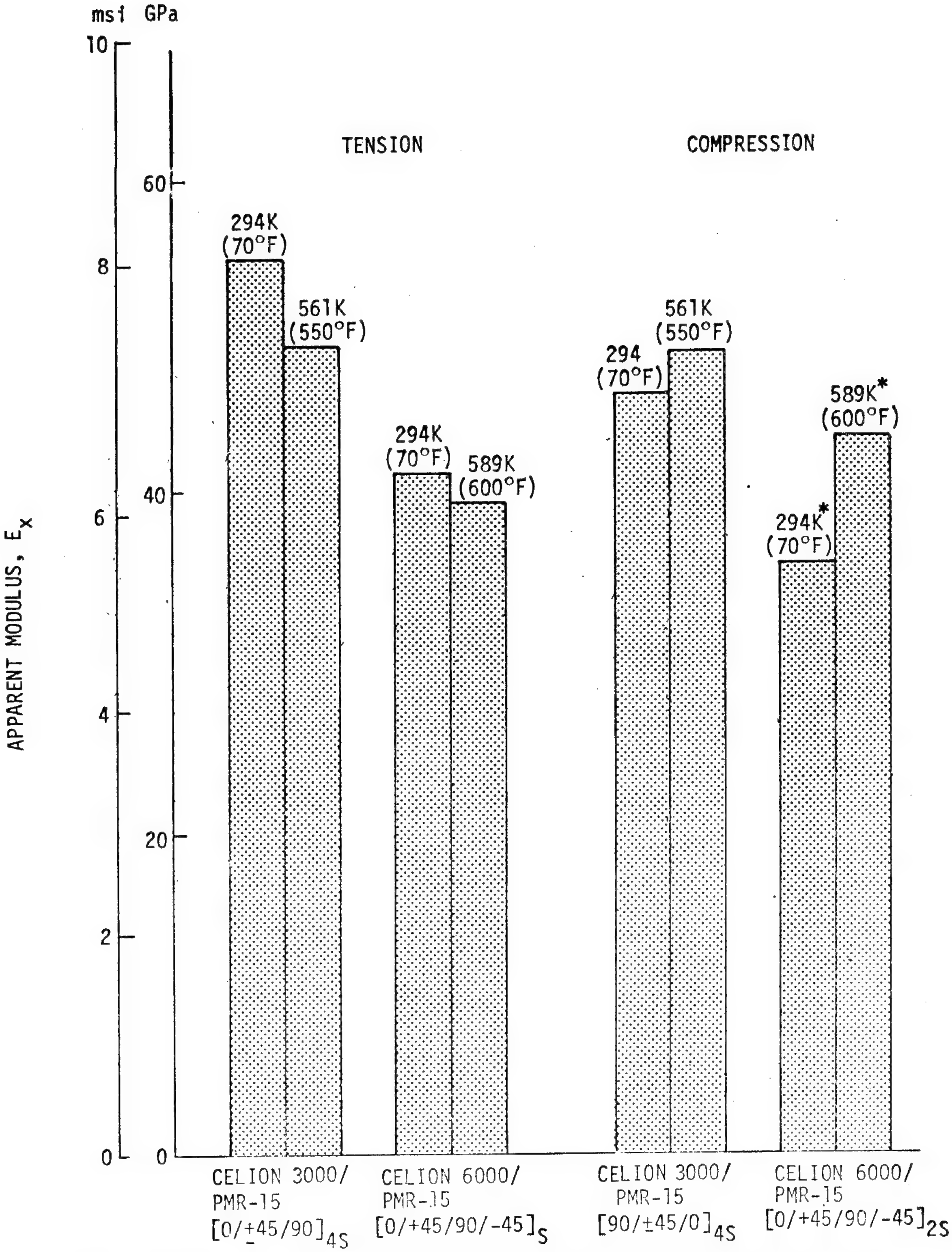
NOTE: Data normalized to 58% fiber volume.

Figure 7.1-1: Design Allowables Comparison Unidirectional Layup



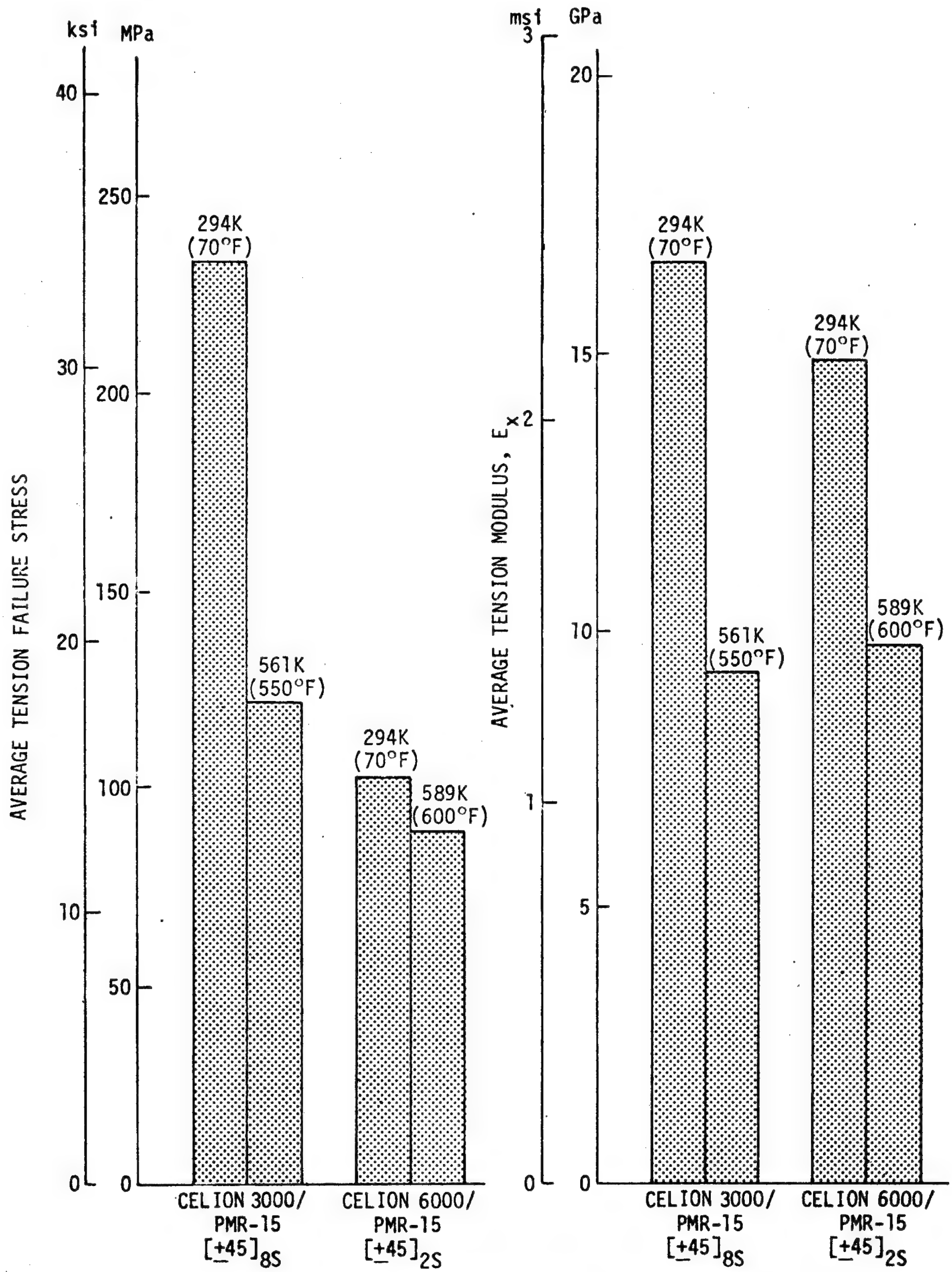
NOTE: Data normalized to 58% fiber volume.

Figure 7.2-1: Design Allowables Comparison
Pseudo Isotropic Layup



NOTES: Modulus data obtained from extensometer output, except as noted.
Data normalized to 58% fiber volume   *Strain Gage Data

Figure 7.2-2: Design Allowables Comparison Pseudo Isotropic Layup



NOTE: Data normalized to 58% fiber volume.
Modulus data obtained from extensometer output.

Figure 7.3-1: Design Allowables Comparison $(\pm 45)_{NS}$ Layup

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8.0 CONCLUSIONS

The following conclusions have been drawn.

1. Celion 3000/PMR-15 and Celion 6000/PMR-15 are processable composites that exhibit sufficient strength at elevated temperatures to make them acceptable as light weight structural materials for high temperature applications.

2. Celion 3000/PMR-15 is slightly stronger than Celion 6000/PMR-15.

3. Compression strengths of $(\pm 45)_{NS}$ laminates using the IITRI fixture may be affected by 'fixity' lateral constraints due to a short test section.

4. Measuring in-plane shear modulus by tension tests of $(\pm 45)_{NS}$ and $(0/\pm 45/90)_{NS}$ laminates is an acceptable test procedure.

5. The CTE of A7F adhesive decreases due to aging.

6. Thermal cycling produces micro-cracking in $(0/\pm 45/90)_S$ Celion 3000/PMR-15 laminates.

7. Moisture has no effect on room-temperature properties but can result in blistering due to rapid heating with subsequent loss of strength at elevated temperature.

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15. Supplementary Notes

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16. Abstract

A design allowables test program was conducted on Celion 3000/PMR-15 and Celion 6000/PMR-15 graphite/polyimide composite to establish material performance over a 116K (-250°F) to 589K (600°F) temperature range. Effects of aging, thermal cycling and moisture were also evaluated. Tension, compression and in-plane shear properties were determined for uniaxial, pseudoisotropic and ±45 laminates. Test results show sufficient strength and stiffness to substantiate graphite/polyimide composites as an acceptable structural material for high temperature structural applications.

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